TRAINING MANUAL I

RADIATION HAZARD CONTROL IN HOSPITALS

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PREFACE

This manual is designed to aid in the training of hospital personnel engaged in work with the more common sources of ionizing radiation. It emphasizes the essentials of safety procedures for users of radioisotopes and X-rays.

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1. ATOMIC STRUCTURE

1.1 Matter

All material is composed of elements or a combination of elements. There are over 100 elements known: of these, some of the heavier ones are man made and do not occur in nature. The smallest unit of any element is an atom of that element. Atoms combine to form molecules. Molecules can be made up of the same element or of atoms of two or more elements as in compounds.

1.2 Fundamental Particles

For the purposes of this manual the atom may be regarded as being composed of three particles: the proton, the neutron and the electron. Their symbols and basic properties are shown in the table below:

Table 1. Properties of the Fundamental Particles

Particle	Symbol	Relative Mass	Electric Charge
proton	p	1 *	+
neutron	n	1	0
electron	e	1/1840	-

*Weight of a proton = 1.67243×10^{-24} gm.

1.3 Structure

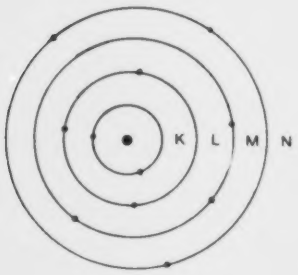
Atoms have a central condensed mass called the nucleus. This is made up of neutrons and protons. The electrons revolve around the nucleus in orbits called shells. The nucleus, which is positively charged due to the protons, and the negatively charged electrons revolving around the nucleus, are subject to an electrostatic force between them. The number of protons in the nucleus is equal to the number of orbital electrons. Therefore the total net charge on the atom is zero.

1.3.1 Electron Shells

There are two restrictions on the atom: one is that there is a limited number of shells allowed and the other is that the total number of electrons in a shell is restricted.

The shells are known by the letters K, L, M, N etc., and the maximum number of electrons in these shells is 2, 8, 18, 32 respectively.

Figure 1. The Atom



• Nucleus
. Electrons

The simplest atom is that of hydrogen which has one proton and one electron in the K-shell. Helium has two protons and two neutrons and a filled K-shell.

Figure 2. The Atoms of Hydrogen and Helium

Hydrogen

Helium

• Proton
° Neutron
. Electron

1.3.2 Atomic Number

The atom of each element has a definite number of protons in the nucleus and it is this number that determines the overall structure of the atom and hence its chemical properties. This number is called the Atomic Number and is represented by the letter "Z".

For hydrogen "Z" is 1, for helium it is 2 while for uranium, which has 92 protons, it is 92. Table 2 gives the atomic number for all known elements.

1.3.3 Mass Number

As will be seen from the relative weights of the fundamental particles, nearly all the weight or mass of an atom is due to the neutrons and protons. The contribution by the electrons is negligible. The sum of the numbers of protons and neutrons is called the Mass Number and is designated by the letter "A", i.e.,

$$A = N + Z \text{ where } N = \text{the number of neutrons}$$

If the mass number and the atomic number are known the N may be determined from:

Table 2. The Elements

Atomic No.	Name of Element	Symbol	Atomic No.	Name of Element	Symbol	Atomic No.	Name of Element	Symbol
1.	Hydrogen	H	36.	Krypton	Kr	70.	Ytterbium	Yb
2.	Helium	He	37.	Rubidium	Rb	71.	Lutecium	Lu
3.	Lithium	Li	38.	Strontium	Sr	72.	Hafnium	Hf
4.	Beryllium	Be	39.	Yttrium	Y	73.	Tantalum	Ta
5.	Boron	B	40.	Zirconium	Zr	74.	Tungsten	W
6.	Carbon	C	41.	Niobium	Nb	75.	Rhenium	Re
7.	Nitrogen	N	42.	Molybdenum	Mo	76.	Osmium	Os
8.	Oxygen	O	43.	Technetium	Tc	77.	Iridium	Ir
9.	Fluorine	F	44.	Ruthenium	Ru	78.	Platinum	Pt
10.	Neon	Ne	45.	Rhodium	Rh	79.	Gold	Au
11.	Sodium	Na	46.	Palladium	Pd	80.	Mercury	Hg
12.	Magnesium	Mg	47.	Silver	Ag	81.	Thallium	Tl
13.	Aluminium	Al	48.	Cadmium	Cd	82.	Lead	Pb
14.	Silicon	Si	49.	Indium	In	83.	Bismuth	Bi
15.	Phosphorus	P	50.	Tin	Sn	84.	Polonium	Po
16.	Sulphur	S	51.	Antimony	Sb	85.	Astatine	At
17.	Chlorine	Cl	52.	Tellurium	Te	86.	Radon	Rn
18.	Argon	Ar	53.	Iodine	I	87.	Francium	Fr
19.	Potassium	K	54.	Xenon	Xe	88.	Radium	Ra
20.	Calcium	Ca	55.	Cesium	Cs	89.	Actinium	Ac
21.	Scandium	Sc	56.	Barium	Ba	90.	Thorium	Th
22.	Titanium	Ti	57.	Lanthanum	La	91.	Protactinium	Pa
23.	Vanadium	V	58.	Cerium	Ce	92.	Uranium	U
24.	Chromium	Cr	59.	Praseodymium	Pr	93.	Neptunium	Np
25.	Manganese	Mn	60.	Neodymium	Nd	94.	Plutonium	Pu
26.	Iron	Fe	61.	Prometheum	Pm	95.	Americium	Am
27.	Cobalt	Co	62.	Samarium	Sm	96.	Curium	Cm
28.	Nickel	Ni	63.	Europium	Eu	97.	Berkelium	Bk
29.	Copper	Cu	64.	Gadolinium	Gd	98.	Californium	Cf
30.	Zinc	Zn	65.	Terbium	Tb	99.	Einsteinium	Es
31.	Gallium	Ga	66.	Dysprosium	Dy	100.	Fermium	Fm
32.	Germanium	Ge	67.	Holmium	Ho	101.	Mendelevium	Md
33.	Arsenic	As	68.	Erbium	Er	102.	Nobelium	No
34.	Selenium	Se	69.	Thulium	Tm	103.	Lawrencium	Lr
35.	Bromine	Br						

$$N = A - Z$$

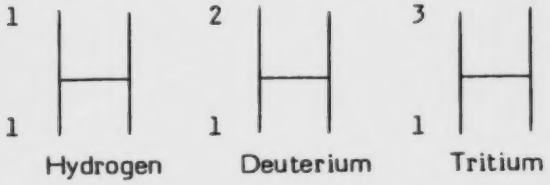
Uranium has a mass number of 238 and its atomic number is 92, thus the number of neutrons is 238 - 92 = 146.

1.4 Isotopes

The number of neutrons per proton in a nucleus i.e., the ratio N/Z, is equal to one in the lighter elements (except hydrogen). This ratio increases with higher values of Z. Nuclear forces between neutrons and protons hold them together. A nucleus of a given element has a characteristic number of protons which requires a certain number of neutrons so that the attractive nuclear forces are enough to counteract the repulsive forces between protons. Although the ratio of N/Z of one gives the optimum stability, the number of neutrons may vary within narrow limits. Thus it is possible to have atoms with the same Z but with a slightly different N and, therefore, a different A. Such atoms of the same element which have different atomic masses or mass numbers are called isotopes.

As has been mentioned earlier, the common form of hydrogen has only one proton in the nucleus. However other forms of hydrogen exist. The nucleus of an atom of a heavier form, called deuterium, has a neutron along with the proton. Such atoms have atomic number 1 but mass number 2. Hydrogen and deuterium are isotopes of the same element. Yet another form with 2 neutrons in the nucleus is known as tritium, with a mass number of 3.

Figure 3. The Three Isotopes of Hydrogen



Many elements have more than one isotope occurring in nature. Unlike hydrogen they are not given special names but are identified by their numbers, for example: Uranium-235 and Uranium-238. The latter contains 3 more neutrons per atom than the former. More complete symbols for these isotopes are $^{235}_{92}U$ and $^{238}_{92}U$, respectively. Such symbols give information about Z, A, and consequently about N.

Except for the isotopes of the very light elements such as hydrogen the behaviour of isotopes of the element are almost identical. It is therefore quite difficult

to separate them from each other by ordinary physical and chemical means. Even for hydrogen, where differences in properties between heavy water and light water are readily measurable, separation procedures are very elaborate.

1.5 Nuclides

All the different types of atoms are referred to collectively as nuclides. A nuclide is a specific type of atom characterized by the makeup of the nucleus i.e., by the number of neutrons and protons it contains. Most of the 90 naturally occurring elements have two or more isotopes. Hence, there are over 300 naturally occurring nuclides. The instability of a radionuclide is due to its nuclear configuration. It tends to decay to a more stable non-radioactive nuclide, as will be discussed in the next chapter.

2. RADIOACTIVE TRANSFORMATIONS AND THE NATURE OF RADIOISOTOPES

2.1 Alpha Particles

When the neutron number for all naturally occurring nuclides is plotted against atomic number, a smooth line is obtained terminating with the nuclides of uranium, the heaviest element (see Figure. 4). Almost all naturally occurring elements whose atomic numbers are higher than 80 and a few of lower atomic numbers have isotopes which are unstable. Due to their large size the nuclear forces holding them together are not quite strong enough to overcome the mutual repulsion of the large number of positively charged protons. Consequently such heavy nuclides undergo nuclear transformation which alter the number of protons and neutrons. This process is called radioactive decay or radioactivity. As the combination of two protons and two neutrons is particularly stable it is often ejected as a unit particle. Such a package, which is identical to the nucleus of a helium atom, is projected with extremely high velocity and is called an alpha particle (α-particle). The remaining nuclide is an atom of an element with atomic number and mass number reduced by two and four respectively. Thus, radium with atomic number 88 and mass number 226 is transformed to radon with Z = 86 and A = 222 or:

$$^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He} + Q$$

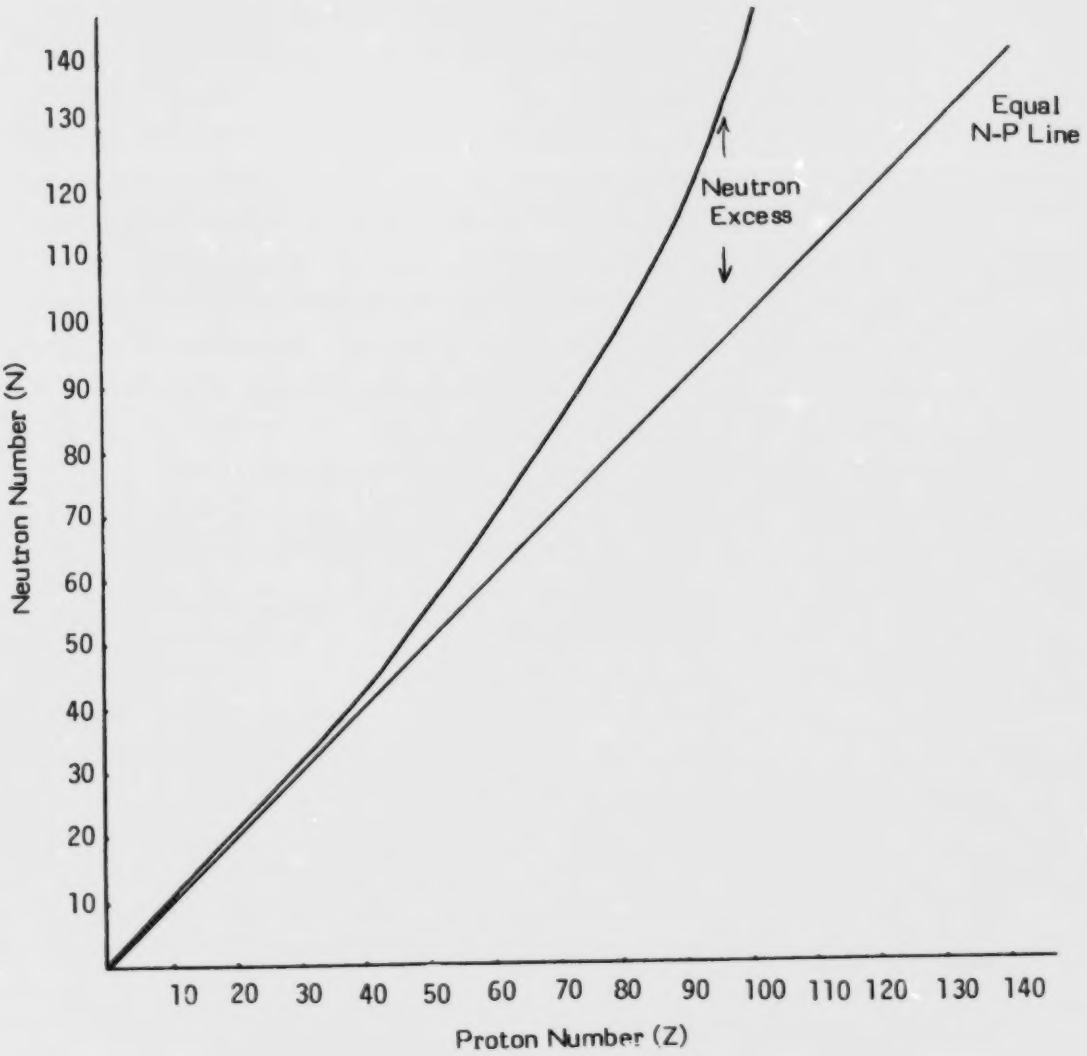
The above is a nuclear reaction equation showing a radioactive transformation whereby one element is transformed into another. In this case "Ra" is the parent and "Rn" is the decay product or daughter. Q represents the energy which is released as kinetic energy of the alpha particle.

Usually, for the heavier elements one such adjustment is not sufficient to establish stability so the process continues in a chain giving rise to a series of radioactive nuclides of decreasing "Z", "N" and "A" until a much lighter, stable element is reached.

2.2 Neutron Emission

Apart from radioactive decay in which alpha particles are emitted, many of the heavier atoms can be induced to split into fragments. Such splitting of a large atom, usually into two heavy fragments is called fission. The most common method of bringing this about is to bombard the heavy nuclide with a neutron. The resulting fission produces further neutrons.

Figure 4. Stability Curve of the Nuclides



Apart from fission there are other methods of producing neutrons. Basically, the only way to produce neutrons is to knock them out of nuclei. This can be done by either energizing a nuclide by gamma radiation or by bombarding it with suitable projectiles. An example of the first reaction, called a photonuclear reaction, is:

$$^{9}_{4}\mathrm{Be} + \gamma \longrightarrow {}^{8}_{4}\mathrm{Be} + {}^{1}_{0}n + Q,$$

where γ is an energetic gamma ray and $^{1}_{0}n$ is the symbol for a neutron.

When α-particles react with certain substances such as beryllium, neutrons are produced by the following reaction:

$$^{9}_{4}Be + {}^{4}_{2}He\ (\alpha\text{-particle}) \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n + Q$$

Such α-neutron sources are prepared by mixing radium and beryllium. The radium provides the α-particles.

2.3 Beta Particles

As seen from Figure 4 the ratio N/Z is an important factor in nuclear stability. If by articifical means a nuclide can be produced with an excess of either neutrons or protons, it would tend to adjust itself to acquire a N/Z value corresponding to stability. To understand the process of doing this, it is necessary to consider the properties of neutrons. The neutron is comparable in mass to a proton. Actually it is slightly heavier. Further, a free neutron will spontaneously change into a proton and an electron, as follows:

$$^{1}_{0}n \longrightarrow {}^{1}_{1}p + e^{-} + \nu$$

where p is a proton, e is an electron and ν is a neutrino with kinetic energy.

Such radioactive decay of neutrons does not normally occur when they are bound in a nuclide. However, if a nuclide has too many neutrons for nuclear stability it adjusts itself spontaneously by converting a neutron to a proton and ejecting an electron. Such ejected electrons which travel at almost the velocity of light are called beta particles (β-particles). Adjustments by this process can continue until the resulting nuclide has a N/Z ratio corresponding to stability.

For each beta emission the nuclide loses a neutron but gains a proton. Therefore, there is an increase in the atomic number by 1 unit but no change in mass number as shown in the following example:

$$^{214}_{82}Pb \longrightarrow {}^{214}_{83}Bi + e^{-} + \nu^{*}$$

where ν^{*} is an anti-neutrino

2.4 K Capture

From the above it can be expected that if an articially produced nuclide has an excess of protons, it will tend to convert a proton into a neutron. One method of achieving this is for the nucleus to capture one of the orbital electrons. Such a process is termed K-capture since an electron in the K orbit is involved. This form of radioactivity does not result in the emission of any particle but there is a release

of energy in the from of electromagnetic radiation due to other orbital electrons filling the vacated electron orbits. Such a transformation results in the daughter having an atomic number less than the parent by 1 unit.

$$ {}^{1}_{1}p + e^{-} \longrightarrow {}^{1}_{0}n + Q $$

2.5 Gamma Radiation

In all nuclear reaction equations, there is a term "Q" required to balance the two sides. This represents the energy released in the reaction. This manifests itself as the kinetic energy carried away by the high speed particles and recoil of the daughter atoms or excess energy carried away by a neutrino.

Many radioactive transformations leave the daughter nucleus in an "excited state". Such nuclei reach the ground state by emission of electromagnetic radiation called gamma rays. Gamma ray emission is, therefore, a secondary effect of a nuclear transformation. The gamma rays emitted have discrete energies, characteristic of the daughter, as they correspond to the energy difference between the two nuclear energy states of the daughter after the primary decay process has taken place.

2.6 Production of Radioisotopes

The production of radioactive nuclei can be achieved by:

1. Splitting up large atoms.
2. Altering the N/Z ratio of a stable nuclide.

The first reaction, namely fission, has already been mentioned: when a heavy atom like uranium splits into 2 fragments, each fragment has a N/Z ratio closely corresponding to uranium. Thus they have far more neutrons than the stable nuclide of corresponding atomic number. To correct this situation the nuclide may initially lose neutrons but subsequently undergoes successive radioactive decay by β-emission. The uranium atom in undergoing fission splits up in a variety of ways producing a large number of such neutron rich fragments. The nuclear reactor where fission of uranium under controlled conditions takes place is therefore a very good source for obtaining radioactive isotopes.

The second method, altering the N/Z ratio of a nuclide, is achieved by bombarding the nuclide with projectiles such as α-particles, protons, neutrons, etc. However, since the nucleus is positively charged, particles such as the proton or α-particle, which are themselves positively charged, will be strongly repelled. Such reactions can therefore be carried out only when the proton or other charged particle is energized to a very great velocity.

If, however, the neutron is used as a projectile, it will not be repulsed by the nucleus since it has no charge. When a material is placed in the path of a beam of neutrons it is expected that some of the nuclei will be hit by the neutrons. Such hits can result in capture by the target nucleus. Capture of neutrons is favored when the neutrons are travelling at a slow rate. These slow moving neutrons are called thermal neutrons. The capturing power of nuclei are quite different for different material. Nuclides which capture neutrons easily are said to have high capture cross sections.

Nuclides which have captured neutrons may have a N/Z ratio greater than required for stability. Therefore, they are likely to be radioactive and decay by emission of α-particles. This method of rendering a material radioactive is the most commonly used for producing isotopes. A neutron capture reaction can be written as follows:

$$^{59}_{27}\mathrm{Co} + ^{1}_{0}\mathrm{n} \longrightarrow ^{60}_{27}\mathrm{Co} + Q$$

2.7 The Radioactive Decay Process

Since radioactive nuclei tend to decay to stable states, it is obvious that the amount of radioactivity will constantly decrease. It has been established experimentally that the rate of decrease is characteristic of the radionuclide and cannot be changed by chemical or physical means. The time required for half the number of any given number of radioactive nuclei to decay is called the half-life of the particular radioisotope. For example, assume that there are one thousand atoms of a certain radioactive substance which has a half-life of ten minutes. After ten minutes there will be only 500 radioactive atoms left. In the next ten minutes half of these 500 would decay leaving 250. This process would continue so that after four half-lives 1/16th of the original radioactive atoms would remain. This process has been shown graphically in Figure 5. It is an exponential curve.

Analytically the number of atoms disintegrating (ΔN) in a given time interval (Δt) is proportional to the number "N" of radioactive atoms present.

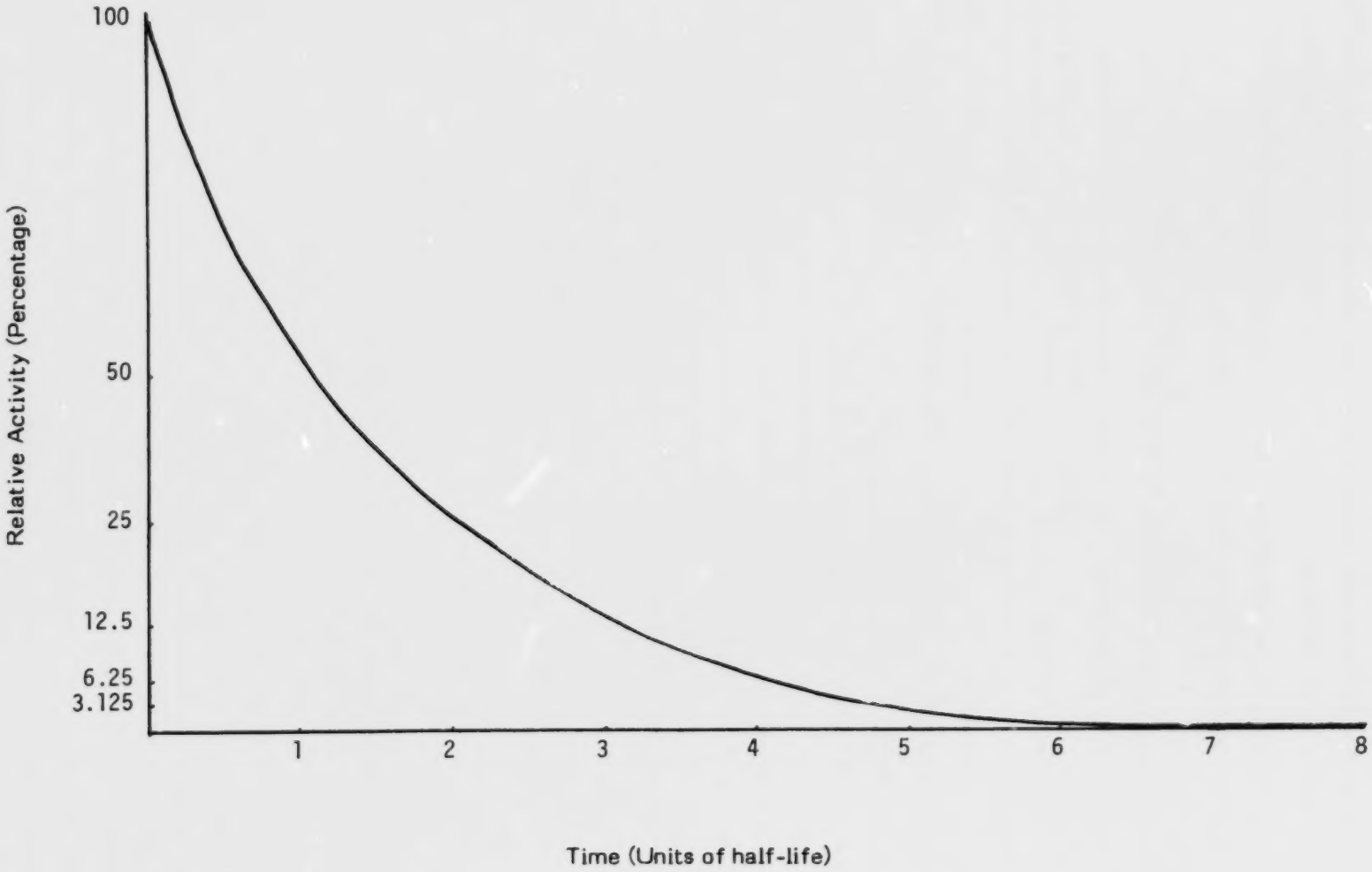
$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Where "λ" is the constant of proportionality called the decay constant. This equation can be integrated to yield

$$N = N_o e^{-\lambda t}$$

where N_o is the total number of atoms present at time "t" = o and N is the number of atoms at time "t".

Figure 5. Decay Curve for Radioactivity



Since this is an exponential equation, the ratio N/N_o plotted against time on semilog graph paper will yield a straight line. The above equation is true for all radioactive decay processes.

The half-life of radioactive isotopes can vary from 10^{-6} seconds to billions of years. Several examples are given in Table 3.

Table 3. Examples of Radioactive Half-Lives

Radionuclide	Half-life	Mass required for 1 curie
Nitrogen-16 (^{16}N)	7.3 seconds	1×10^{-11} grams
Strontium-90 (^{90}Sr)	19.9 years	7×10^{-3} grams
Radium-226 (^{226}Ra)	1622 years	1 gram
Uranium-238 (^{238}U)	4.49×10^{9} years	3×10^{6} grams

3. CHARACTERISTICS OF RADIATION

3.1 Introduction

The most common types of radiation emitted as a result of radioactive transformation are α-rays, β-rays, and γ-rays. All these radiations interact in different ways when passing through matter. However, in every case the most important effect on matter is ionization. When an atom loses an electron it becomes positively charged. This charged atom is called an "ion". The electron knocked off is negative. This process of creating an ion pair is called ionization:

$$A \longrightarrow A^{+} + e^{-}$$

3.2 Alpha particles

The heaviest of the common types of ionizing radiation are alpha particles.

Alpha particles are very highly ionizing as they pass through matter because of their charge and momentum. This fact is of particular significance when they strike living cells. One favourable property of these particles from a health and safety point of view is that they are the least penetrating of all radiations commonly encountered. A few centimeters of air or a thin piece of paper is sufficient to completely absorb these particles. The range in matter of the alpha particle is proportional to its energy or velocity. The usual values of alpha particle energies are between 4 and 9 MeV. Some examples from the uranium series are:

U-238	4.200 MeV
Rn-222	5.486 MeV

The energy of alpha particles emitted by a given radionuclide is specific and characteristic of that isotope.

As the alpha particles, which are positively charged, pass through gas or air, they strip loosely bound electrons from the atoms and create ion pairs. The creation of one ion pair requires approximately 35 electron volts. Therefore, as the alpha particle progresses, it ionizes the gas and loses energy. As the alpha particle slows down, it spends a longer time in the region of each atom, and has a much better chance of ionizing them. Therefore, the intensity of ionization increases as the alpha particle is slowed down. The specific ionization goes up rapidly and finally drops to zero as the particle comes to rest. When the alpha particle is stopped, it collects two electrons to form a helium atom. The distance in air at which the alpha particles are stopped is known as the alpha particle range. Over the range of an alpha particle of energy 7.68 MeV approximately 220 000 ion pairs are formed.

3.3 Beta Particles

Beta particles are fast moving electrons emitted during radioactive decay. Their velocity approaches the speed of light. They have a continuous spectrum of energy from zero to a maximum energy, Emax. This maximum energy is characteristic of a particular radioisotope. Beta particles are absorbed by a few millimetres of aluminium or similar material. They will travel several hundred centimetres in air before they expend their energy.

Beta particles may be scattered out of a beam either by collisions with other electrons, or they might make multiple elastic collisions and lose much of their energy to the absorber.

Beta particles may be slowed down by interacting with the electric field of a nucleus or the atomic electrons. When this occurs some of the particle's energy is transformed into X-radiation. This radiation appears as a continuous spectrum and is called bremsstrahlung (braking radiation). The maximum energy of the X-rays produced will be equal to the maximum energy of the beta particles and corresponds to the electrons losing all their kinetic energy in one interaction.

The amount of energy lost by bremsstrahlung production is usually only a few percent but it is proportional to the energy of the particles and the atomic number of the material.

Energy values for beta particles range from 18 keV for Tritium to 4.81 MeV for Cl-38. When referring to energies of beta particles, the maximum energy is quoted.

3.4 X-Rays and Gamma Rays

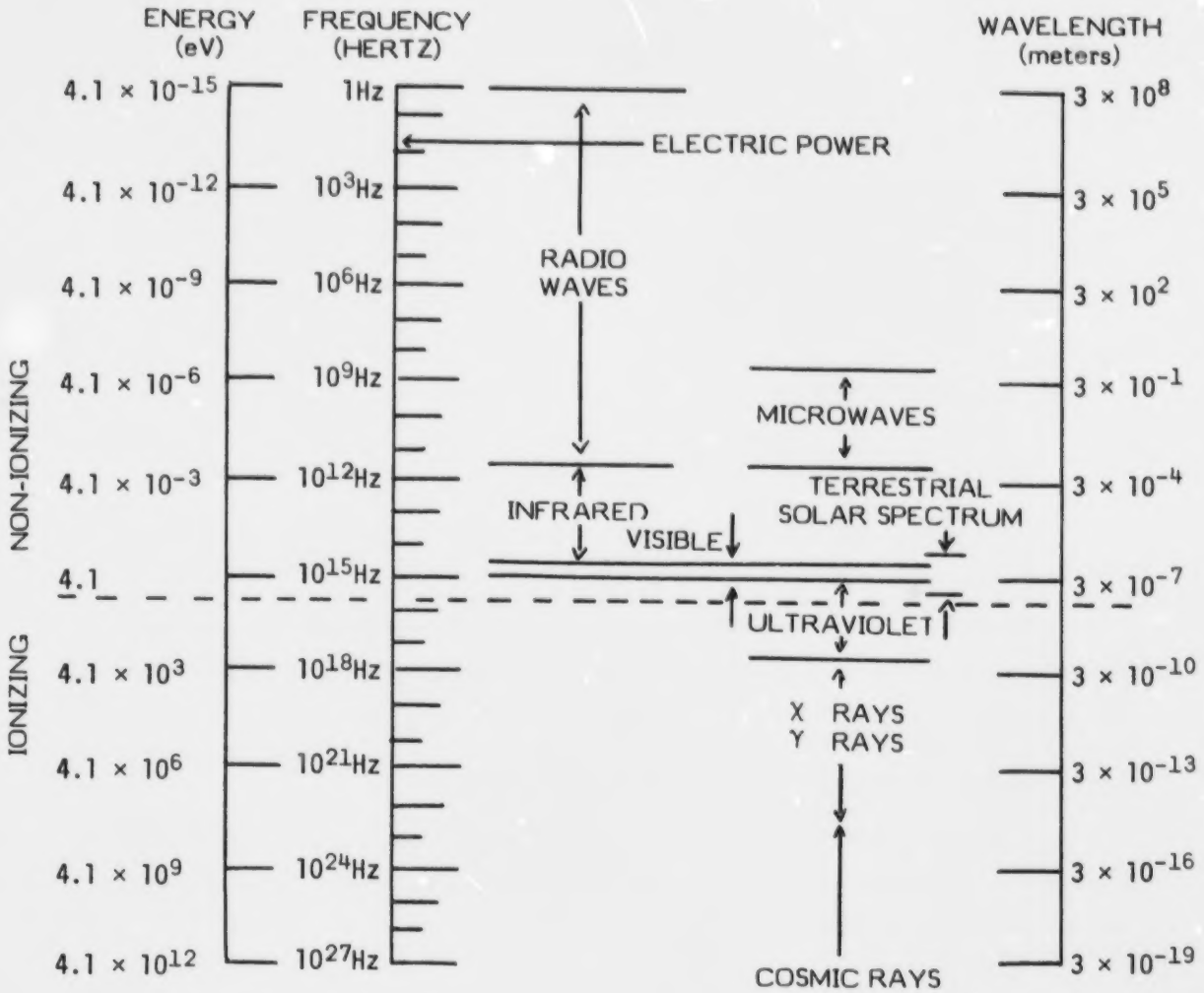
The radiation emitted from radioactive substances is of two types: particles and electromagnetic radiation. Alpha and beta radiation are particulate and X-rays and gamma rays are electromagnetic radiations. Electromagnetic radiation can be thought of in terms of packets of energy or "photons". Each photon carries a specific quantum of energy.

X-rays and gamma rays have identical energy but differ in their origin. They will be discussed in greater detail in subsequent chapters.

3.5 Electromagnetic Spectrum

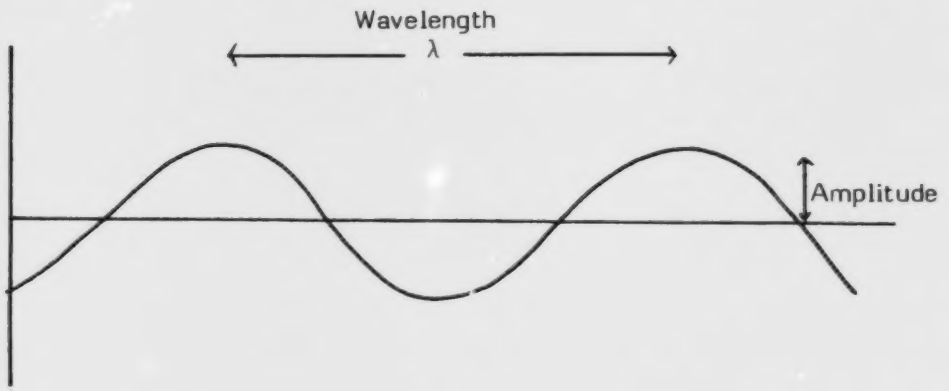
Other types of electromagnetic radiation are visible light, radio waves, infrared and ultra violet. As can be seen from Figure 6 there is an enormous energy difference between high energy gamma or X-radiation and low energy radio waves.

Figure 6. Electromagnetic Spectrum



It is useful to think of electromagnetic radiation in terms of waves (see Figure 7 below). This is most applicable when one is dealing with a very large number of photons, as in the case of visible light, rather than individual high energy photons, such as gamma rays.

Figure 7. Wave Motion



The distance between two crests or troughs is called the wavelength (λ).

All electromagnetic radiations travel at the same velocity in a vacuum regardless of wavelength. This velocity is equal to 3×10^{10} cm/sec.

Frequency is the number of waves which go past a given point per second. The relationship between frequency, wavelength and velocity is given by the equation:

$$C = \lambda\nu$$

where C = velocity, λ = wavelength, ν = frequency

The energy of electromagnetic radiations exists in small "packets" or photons. The amount of energy in each photon is directly related to the frequency as shown in the following equation:

$$E = h\nu$$

where "h" is a constant for all electromagnetic radiations, known as Planck's constant.

4. NATURE AND PRODUCTION OF X-RAYS

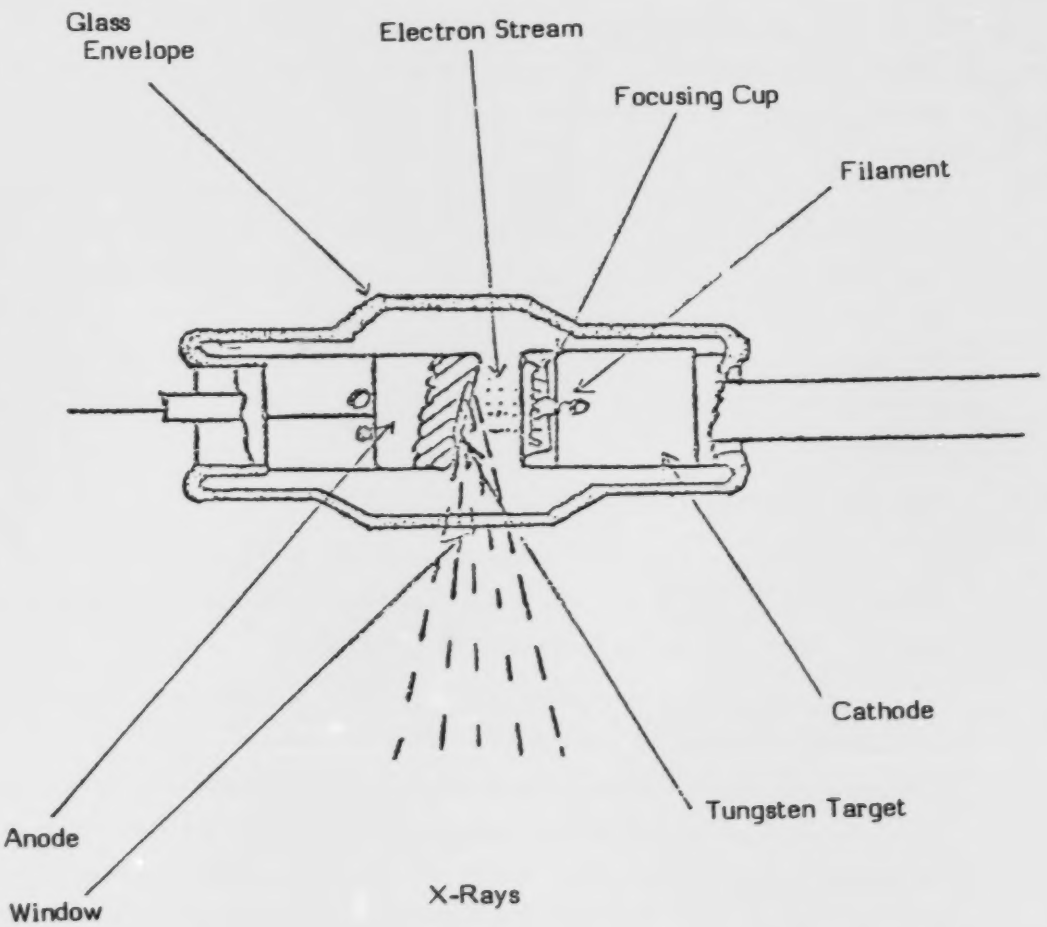
4.1 Introduction

X-rays are produced when high speed electrons bombard a target material. The target material is made up of atoms of a heavy element, such as tungsten, in the form of a solid.

The main components of an X-ray unit are:

i. a source of electrons called the filament or cathode;
ii. an evacuated space in which to accelerate the electrons;
iii. a high positive potential to accelerate the electrons; and
iv. a target, or anode, which the electrons strike to produce X-rays. (Figure 8).

Figure 8. Stationary Anode Tube



The temperature of the filament or cathode determines the number of electrons accelerated toward the anode and the accelerating voltage, called the kilovolt peak (kVp) determines the maximum energy of the X-ray photons produced.

The intensity of the X-ray beam produced when the electrons strike the anode is dependent upon the nature of the target material. X-rays are efficiently produced if the atomic number (Z) of the target is high. The target material should also have a high melting point since heat is produced when the electrons are stopped in the surface of the target.

Nearly all modern X-ray tubes use tungsten as a target material. The Z of tungsten is 74 and its melting point is 3400°C.

4.2 Production of X-Rays

The energy of most of the electrons striking the target is dissipated in the form of heat, however, the remaining few electrons produce useful X-rays.

The spectrum of X-rays produced by a modern X-ray unit is shown in Figure 9. The broad smooth curve is due to the bremsstrahlung or continuous X-rays and the spikes represent the characteristic or line X-rays.

4.2.1 Continuous X-rays

Continuous X-rays are produced when the fast moving electrons are abruptly slowed down as they collide nearly head-on with the strong coulomb field of the nucleus. Since the electron is deccelerated, energy is radiated. This emitted energy takes the form of X-rays called bremsstrahlung or continuous X-rays. When large numbers of electrons are involved, the radiated energy has a spectral distribution as shown in Figure 10.

4.2.2 Characteristic X-rays

Characteristic or line X-rays appear in the spectrum as sharp peaks superimposed on the continuous spectrum. These peaks or lines are uniquely characteristic of the element that is used as the target of the X-ray tube.

A photon of bremsstrahlung radiation or an incoming electron interacts with a K electron in the target atom and knocks it out of its orbit and free of the atom. The vacancy in the K shell is filled immediately when an electron from an outer shell falls into it. A characteristic K X-ray photon is therefore emitted which carries off the excess energy between the L and K electron orbit. An X-ray photon can also be emitted if an electron falls from the L level to the K level or from the M shell to

Figure 9. The X-ray Spectrum

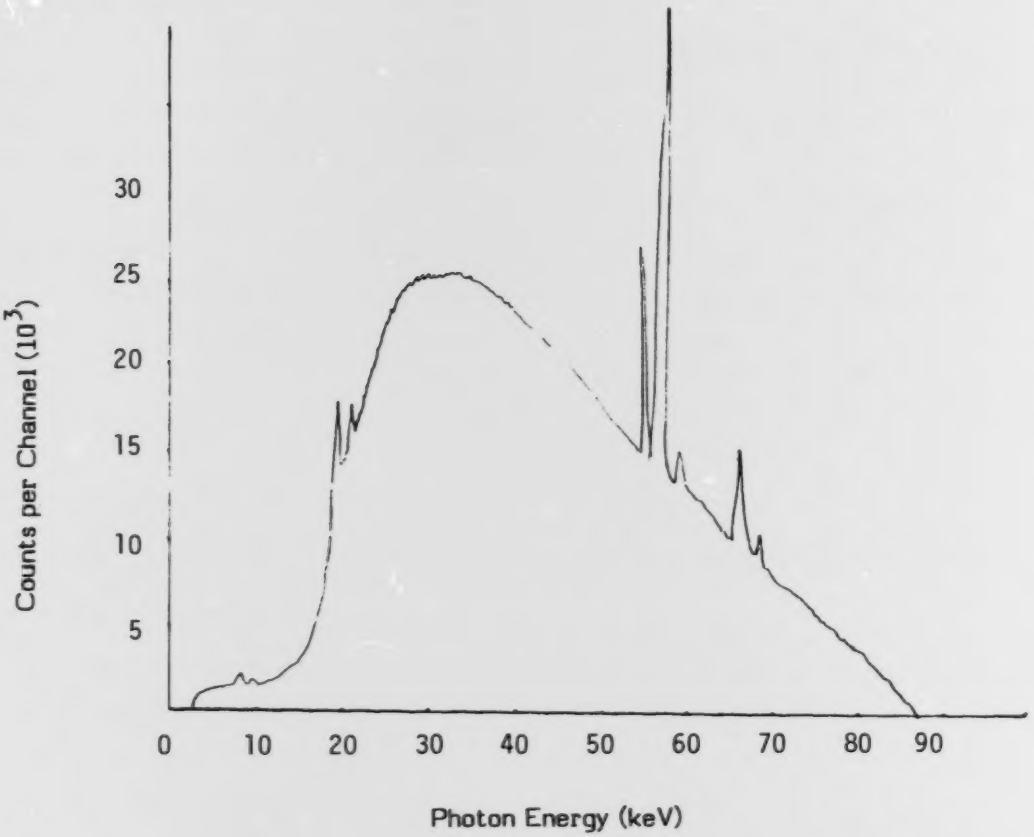
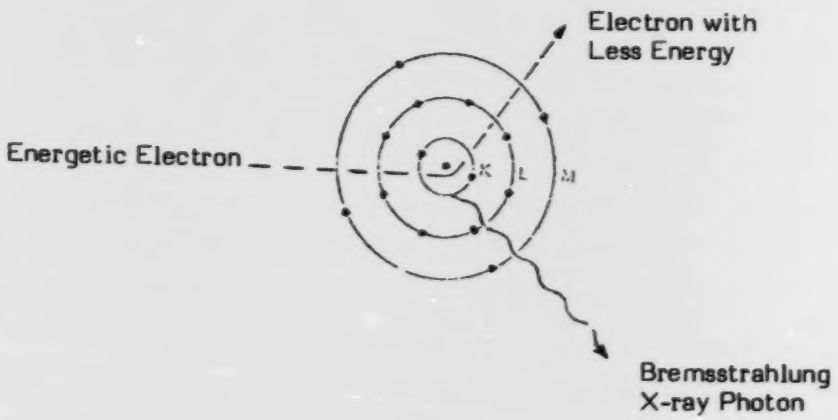
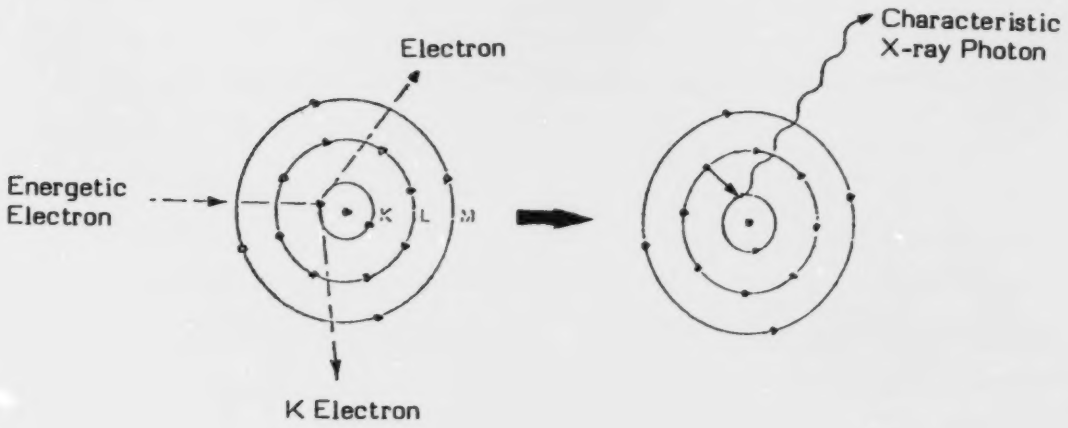


Figure 10. Production of Continuous X-rays



the K shell. Since the energies of the electrons in the various shells are precisely determined, an electron falling from an outer shell to an inner shell will always produce an X-ray with an energy characteristic of that atom, and corresponds to the difference in the orbital energies.

Figure 11. Production of Characteristic X-rays



5. INTERACTION OF X-RAYS AND GAMMA RAYS WITH MATTER

5.1 Introduction

The behaviour of electromagnetic radiation is dependent upon wavelength. When radiation of long wavelength, such as light or heat, strikes matter it may be partially reflected or may transfer its entire energy in the form of heat. X-rays and gamma rays have much shorter wavelengths and are, therefore, very penetrating.

X-rays are not absorbed equally well by all materials. Heavy elements such as calcium are much better absorbers of X-rays than light elements such as carbon, oxygen and hydrogen.

The attenuation of an X-ray is its reduction in intensity as a result of absorption and scattering of some of the photons out of the beam.

5.2 The Mechanism of X-Ray and Gamma Ray Interaction

There are 3 ways an X-ray or gamma ray can interact with atoms.

5.2.1 The Compton Effect

In this process the incident photon interacts with a "free" electron, transfers some of its energy to the electron (recoil electron) and is scattered. An electron is termed "free" if the energy of the interacting photon is considerably greater than its binding energy, i.e., it is a loosely bound electron.

The scattered photon will have a lower energy (and therefore a longer wavelength) than the incident photon. The recoil electron takes up the difference of energy between the incident and scattered photon and is ejected. This electron is called a Compton electron.

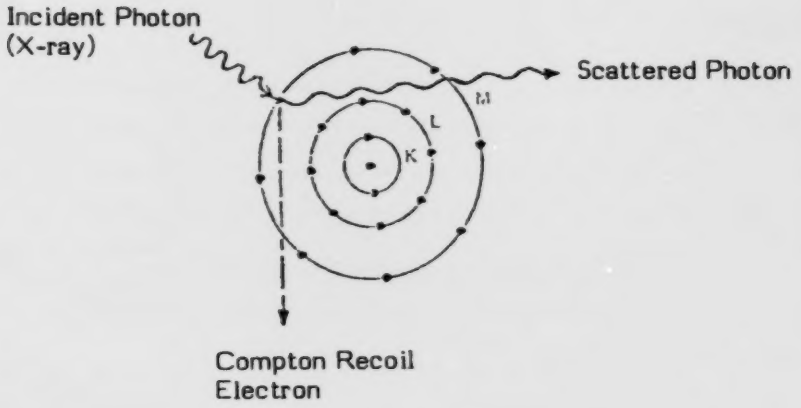
5.2.2 The Photoelectric Effect

In this process the photon collides with an orbital electron and transfers all of its energy to this particle by ejecting it from the atom.

If the energy of the photon is more than is required to eject the electron from the atom, the ejected electron is given additional energy in the form of kinetic energy. This is known as the photoelectric effect and electrons ejected by this process are known as photoelectrons. This process completely absorbs the energy of the incident photon.

The ejection of an electron from a shell will leave a vacancy. This will be filled by an electron from another shell with the emission of an X-ray with an energy

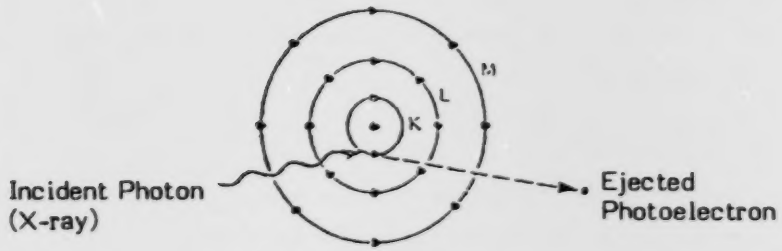
Figure 12. The Compton Effect



Energy of Photon = Energy of Scattered Photon + Energy of Recoil Electron

corresponding to the difference in the binding energy of the two shells. The resulting vacancy will itself be filled and the sequence repeated until an electron from outside the atom is trapped. The X-rays are emitted in ranJom directions, and the process is very similar to the characteristic X-rays produced in an X-ray tube.

Figure 13. The Photoelectric Effect



Energy of Photon = Binding Energy of Electron + Kinetic Energy of Electron

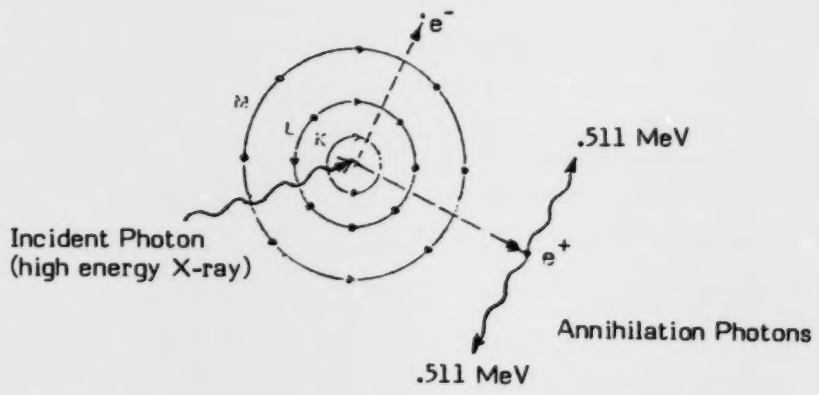
5.2.3 Pair Production

Neither the Compton nor the Photoelectric effect contribute very significantly to the absorption of high energy gamma rays. In the high energy region pair production accounts for the majority of the photon absorption especially in elements of high atomic number. This process requires a minimum energy of 1.02 MeV as a threshold. (1 electron mass is equal to 0.51 MeV).

Pair production involves the complete disappearance of the incident photon and the creation of a pair of electrons, one positive and one negative. In the process of pair formation all of the photon's energy is given up to the electron pair. Energy supplied in excess of 1.02 MeV is shared by the pair in the form of kinetic energy.

The electron and positron lose their kinetic energy by ionization and excitation. The positron interacts with an electron and annihilation occurs with the creation of two .51 MeV photons travelling at 180° to each other.

Figure 14. Pair Production



5.3 Attenuation

The net result of these three interactions is that a beam of photons passing through a material is attenuated. The amount of attenuation is proportional to the thickness of the absorber and can be mathematically expressed as:

$$I = I_{1_o} e^{-\mu X}$$

where: I_o is the initial intensity

I is the intensity after penetrating a distance X in the medium

μ is the linear absorption coefficient

e is the exponential constant.

For calculating shielding requirements, it is usually sufficient to use so-called half-value layers (HVL) and tenth-value layers (TVL) which for a particular material and radiation is the thickness of absorber that is required to attenuate a beam of radiation to one-half and one-tenth of its initial value respectively. These can be mathematically expressed as.

$$I = I_o/2^n$$
$$I = I_o/10^n$$

where "n" is the number of HVL or TVL respectively.

The approximate values of TVL and HVL for various materials for different radiations are shown in Table 4.

Table 4 Approx. TVL and HVL for Shielding
(Thickness in Centimeters)

Source	Lead		Iron		Concrete	
	TVL	HVL	TVL	HVL	TVL	HVL
X-Rays						
100 KVP	.08	.02	.83	.25	5.84	1.77
150 KVP	.10	.03	1.11	.33	7.62	2.28
250 KVP	.25	.08	3.04	.99	9.14	2.79
400 KVP	.76	.22	8.38	2.54	10.92	3.30
500 KVCP	1.27	.38	13.97	4.06	11.68	3.55
1000 KVCP	2.54	.81	20.32	6.35	15.24	4.57
2000 KVCP	3.81	1.27	26.67	8.89	20.32	6.22
Co-60	4.11	1.24	7.36	2.20	22.86	6.85
Ra-226	4.69	1.42	7.69	2.31	24.38	7.36
Cs-137	2.13	.63	5.71	1.72	18.03	5.33
Ir-192	1.62	.48	-	-	15.74	4.82

6. UNITS USED FOR RADIATION WORK

It is necessary to understand the various units for measuring different radioactive quantities and to understand the interrelationships that exist. Definitions of all the units are given in the Glossary of Technical Terms. In what follows, the more important ones are discussed.

6.1 Units for Measuring Radioactivity

The unit of radioactivity, the curie, was initially established as that amount of activity corresponding to one gram of radium. One curie of activity is equal to 3.7×10^{10} disintegrations per second. Under the International System of Units (SI), now adopted by Canada, the unit of radioactivity is the becquerel (Bq). One becquerel is equal to one distintegration per second. Therefore, one curie (Ci) is equivalent to 3.7×10^{10} Bq., or 1 Bq is equivalent to 27.03×10^{-10} Ci.

6.2 Units of Radiation Energy

A. While the becquerel gives information about the number of disintegrations, it does not indicate the energy of the radiation being emitted. The unit used for this purpose was electron volt. The SI unit is the joule.

$$1eV = 1.6 \times 10^{-19} \text{ J}$$

One electron volt is equal to the energy gained by an electron in passing through a potential difference of one volt. Since the charge of the electron is very small, the electron volt represents a very tiny amount of energy. The energy of the radiations used in radiography are expressed in million electron volts, abbreviated as MeV. One MeV is equivalent to 1.6×10^{-13} J.

B. The energy of X-radiations is often expressed in terms of kVp. This is an abbreviation of kilovoltage peak and refers to the peak potential of the high voltage in the X-ray machine. It is not a direct measure of the energy of the radiation, but since energy and tube voltage are related, it gives an indication of the energy of the radiation. The quality of an X-ray beam can also be described by its half-value layer (HVL). The HVL is that thickness of some specified material, (usually Al or Cu) which will attenuate the beam to one-half its original intensity. The HVL of a beam is a function of its effective energy. The effective energy in keV units is approximately 1/3 of the applied potential, being influenced somewhat by the nature of the power supply, and increasing as filtration is added.

6.3 Units of Radiation Dose

The most important characteristic of alpha, beta, gamma and X-rays is their ability to ionize the atoms and molecules of the material through which they pass. The unit for measuring intensity of gamma or X-radiation is based upon its ability to produce ionization. This unit was the roentgen, now replaced by coulomb/kg.

A. Coulomb/kg (roentgen)

This unit of exposure dose was the roentgen and is based upon the ionization of air. It is that quantity of radiation that results in the production of 1 e.s.u. of charge in 1 cubic centimetre of air at S.T.P. expressed in coulombs per kilogram.

$$1 \text{ coulomb/kg} \sim 3876 \text{ roentgen}$$

B. The Gray (rad)

Since the roentgen is not easily applicable to all systems, a unit of absorbed dose is used when considering radiation damage in living tissue. The unit is the gray (Gy) and is equal to 1 joule per kilogram. The old unit was the rad which was 1/100th of the Gy, i.e., 1 Gy = 100 rads = 1 J.kg^{-1}.

C. Quality Factor (RBE)

RBE stands for Relative Biological Effectiveness. Different ionizing radiations can cause different amounts of biological damage for the same gray dose delivered. Examples of this are alpha radiation and fast neutrons both of which cause more damage than commonly used gamma and X-radiation. The RBE for gamma and X-radiation used in radiography is equal to 1. This has been replaced by the "Q" or Quality Factor.

D. The Sievert (rem)

The rem was an abbreviation of roentgen-equivalent-man and was related to the rad by the equation:

$$\text{REM} = \text{RAD} \times \text{RBE}$$

For gamma and X-radiation the RBE is one, therefore the rem dose and the rad dose are the same. For other types of radiation, quality factors are incorporated into the equation, which then becomes:

$$H = D \times Q \times N$$

where: H = dose equivalent in sieverts

D = absorbed dose in grays

Q = quality factor

N = an estimate of all other modifying factors

The name for the unit of dose equivalent is the sievert (Sv) which replaces the rem. The sievert has the units of $1\ J.kg^{-1}$, the same as the Gy.

$$1sv = 100\ rem$$

7. BIOLOGICAL EFFECTS OF RADIATION

7.1 Introduction

The basic changes that occur in the interaction of radiation with matter are identical in living and non-living material. All radiation injury results primarily from radiation induced chemical changes in one or more of the complex molecules present in living cells. These changes may be reversible or may lead in due course to cell death or transformation.

The cell is about 70% water and surrounded by inorganic molecules such as NaCl and large molecules of organic acids and proteins. The nucleus of the cell contains a fixed number of chromosomes made up of a large number of genes which determine the structure and function of the cell.

7.2 Intracellular Events

The effects of ionizing radiation at the cellular level determine the effect on the whole animal.

Figure 15 illustrates the sequence of events that occur within a cell upon exposure to radiation.

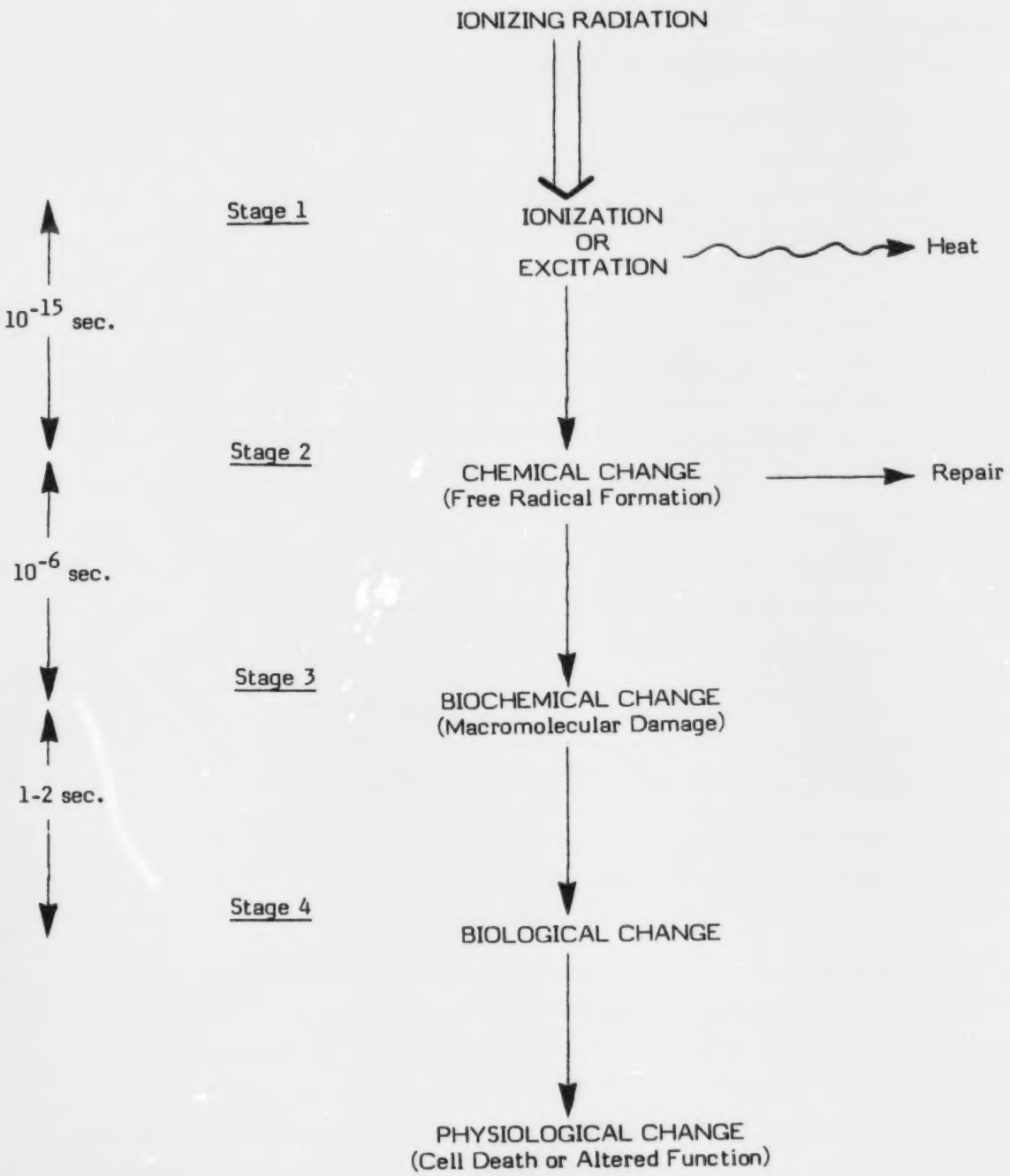
The first phase of the induction of radiation injury is the shortest, lasting about 10^{-15} seconds. During this phase energy is deposited in the cell causing ionization and excitation of ions and molecules. The amount of heat produced by these ionizations is negligible and has no biological effect.

The ionization of the target molecule directly is called the Direct Effect. This occurs when a photon or particle ionizes a DNA constituent directly without the production of intermediate reactive water or O^{+} ions. If the intermediate ions are produced then it is called the Indirect Effect. The principal products of the radiation absorption are hydrogen, hydroxyl ions, and free radicals. Hydrogen and hydroxyl ions are normally present in living cells and do not contribute to radiation damage. The free radicals, however, which contain unpaired electrons, are very highly reactive. The time involved for the production of free radicals, i.e., stage 2, is about 10^{-6} seconds.

As indicated in Figure 11 the biochemical changes at this point may be rectified, often by recombination, leading to repair and no obvious damage. However, if repair does not occur the sequence of intracellular events includes a third stage.

In the third stage, lasting a few seconds, the free radicals react with organic molecules. Reactions with proteins and the deoxyribonucleic acid (DNA) of the cell

Figure 15. Sequence of Intracellular Events



nucleus are particularly important, producing changes in the secondary or tertiary structure of proteins. These changes may produce alterations in the biological properties of the molecules. The breaking or crosslinking of DNA molecules may have effects which may lead to cancer or the birth of genetically damaged offspring.

The last phase of the induction of radiation injury is the biological phase during which the chemical changes are transformed into cellular changes i.e., early cell death, prevention or delay of cell division and the production of permanent, inheritable changes.

7.3 Somatic Effects of Radiation

The somatic effects of radiation arise mainly from interference with the processes of cell division. Therefore, acute damage is most likely to be observed in those cells undergoing rapid cell division such as the cells of the lymphoid and granulocyte systems and the cells lining the gastrointestinal tract.

Following exposure to 25 rads or more the lymphocyte count in the peripheral blood falls rapidly. The platelet count and the red blood count in the peripheral blood also fall a few days after exposure and then recover if the radiation dose received is not too large. Blood counts are used extensively to monitor patients undergoing radiation therapy. In addition, blood counts and cytogenetic studies are used in the assessment of persons occupationally overexposed.

The biological effects of radiation which arise a long time after the radiation dose is received include types of cancer, cataract formation and life-shortening.

7.4 Genetic Effects of Radiation

The genetic effects of radiation arise from radiation induced mutations that occur in the egg cells of the female or in the sperm cells of the male. The most severe genetic damage probably results in embryonic or foetal death.

7.5 Dose Response Curves

In order to establish acceptable levels of exposure, it is useful to correlate the dosage received with the response or damage produced.

Figure 16 below is a typical threshold curve. The point at which the curve intersects the X-axis is the threshold dose, i.e., the dose below which there is no effect. If an easily observable radiation effect such as reddening of the skin is taken as a response, then this type of curve is applicable.

The first evidence of the effect does not occur until a certain minimum dose is received. These types of radiation effects are called the non-stochastic effects.

Figure 16. Threshold Curve

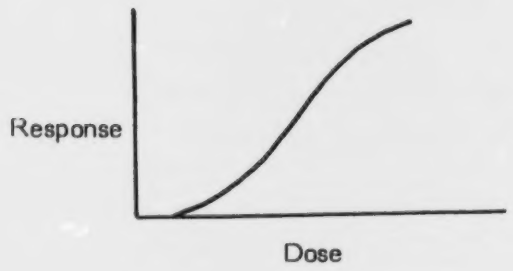
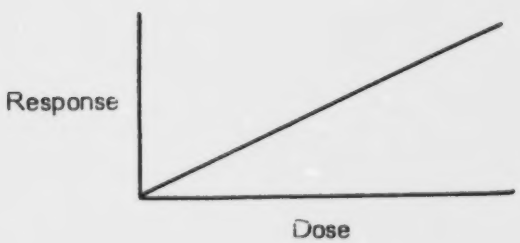


Figure 17 represents a linear, non-threshold relationship in which the curve intersects the origin. Here it is assumed that any dose, no matter how small, involves some degree of response, i.e., there is no threshold. These types of effects are called stochastic effects. The genetic and cancer inducing effects of radiation are examples.

Figure 17. Non-Threshold Curve



7.6 Human Exposure To Radiation

If the non-threshold hypothesis is assumed, then all radiation exposure is potentially harmful. In the case of the radiation worker, the patient undergoing radionuclide or radiographic investigations and the general public at large, it is necessary to prescribe radiation dose levels at which the risk of serious injury to the individual is so low that it may be acceptable to the individual and society in general.

In 1928, the International Commission on Radiological Protection (ICRP) was created to advise on all aspects of radiation protection and make recommendations concerning basic principles and radiation dose limits. They ensure that no source of radiation exposure is unjustified in relation to its benefits, that any necessary exposures are kept as low as is reasonably achievable (ALARA principle) and that exposures by individuals do not exceed specified limits.

The estimates of gonad doses to the general population from various sources of radiation are:

Background -1 m Sv/yr (100 mr/yr)
Medical and other - 1 m Sv/yr (100 mr/yr)
Fallout - .2 m Sv/yr (20 mr/yr)

The maximum permissable gonad or whole body dose allowed in Canada for the general population is 5 mSv/yr (.5 rem/yr).

The maximum permissible gonad or whole body dose allowed in Canada for atomic radiation workers is 50 mSv/yr (5 rem/yr) not to exceed 30 mSv (3 rem) per quarter of a year.

8. USES OF RADIOISOTOPES IN MEDICINE

The uses of radioisotopes in medicine can be broadly classified into two categories: unsealed sources and sealed sources.

8.1 Unsealed Sources

The ultimate fate of radionuclides entering the body depends on their chemical properties and on their interactions with the natural components of cells and tissues. Some materials may be widely distributed throughout the body while others may localize in specific organs or tissues. The radionuclides of iodine concentrate in the thyroid gland, while those of calcium and radium deposit mainly in the skeleton. The retention of radionuclides in the body may vary widely from complete elimination within a few hours to retention times of many years, depending on the chemical and physical properties of the deposited material.

In nuclear medicine when unsealed radionuclide sources are used, radioactive material may enter the body accidentally by swallowing; inhalation of gases, aerosols or dusts; or through the skin or a wound. For this reason the maximum benefit from these diagnostic and therapeutic tools can only be derived if the hazards, in addition to the advantages, are well understood.

Unsealed or open sources are mainly used as tracers in medicine. There are several properties of isotopes which make them very useful as tracers:

i. isotopes of any element, whether radioactive or not, behave identically in physical and chemical reactions;

ii. very small quantities of a radioisotope can be detected and accurately estimated without much difficulty;

iii. radioisotopes can be quantitatively estimated without having to destroy the material being analysed.

These properties have led to the use of a variety of radioisotopes in medicine. A good example is that of radioactive iodine for the diagnosis and treatment of thyroid disorders. The hormone produced by the thyroid is rich in iodine and in a normal person between 15% and 40% of the iodine intake reaches the gland within 24 hours. Therefore, if radioactive iodine is ingested and its path followed, the measure of radioiodine uptake by the thyroid gland is a good indicator of thyroid function. In addition, large doses of radioiodine can be used to treat thyroid malignancies.

Almost every body function has been studied with the use of radioactive tracers. Organs which can be scanned with isotopes include the lung, skeleton, liver, spleen, brain and kidney. In addition, isotopes have been used for dynamic studies of the function of the kidney, liver, heart, intestines and lungs. Radioisotopes such as iron, chromium, cobalt and iodine are used to measure blood volume, and to study anemia and other blood disorders.

8.2 Sealed Sources

Sealed sources are radioactive materials enclosed in durable capsules designed to withstand normal handling. The destructive effect of radiation can be utilized for the killing of malignant cancer cells. Fortunately, many cancer cells are more easily damaged than normal cells, and so radioactive sources are extensively used in cancer therapy.

The first isotope to be used was radium. This has been replaced with cesium in North America. Treatment is carried out by placing a source of cesium, in the form of a needle or tube, in the vicinity of the cancerous growth. However, in many forms of cancer the preferred mode of irradiation is teletherapy treatment at a distance. For this form of treatment, methods have been devised to deliver massive doses to the tumour while exposing healthy tissues to relatively low doses. Teletherapy machines are loaded with ^{60}Co, an isotope with penetrating gamma radiations, half-life of 5.2 years and relatively cheap to produce. X-rays and various types of high energy particle accelerators are also used for radiation therapy.

For certain forms of skin cancers β-emitting isotopes in the form of sealed sources are used. Strontium-90 plaques are commercially available for such purposes.

9. LABORATORY FACILITIES FOR THE HANDLING OF RADIOISOTOPES

9.1 Introduction

The design of a laboratory for handling radioactivity will vary enormously, from a designated bench in a normal chemical or pathology laboratory to a specially designed and built radiation laboratory. In a hospital with a nuclear medicine facility there is an additional requirement for pharmaceutical safety when radiopharmaceuticals are being prepared and dispensed.

The hazards associated with radionuclides will depend on the procedure carried out, the toxicity of the radioactive compound and the activity involved. The International Atomic Energy Authority (IAEA) has divided the common radionuclides into various classes of toxicity and laid down limits of activity for each class which may be handled in three grades of laboratory (A, B, and C).

The four categories of radiotoxicity are listed in Tables 6-9.

The grade of laboratory required for the various activities of radionuclides of different toxicities is indicated in Table 5 below.

Table 5. Types of Laboratories

Radiotoxicity of Isotope	Type of laboratory required for levels of activity specified below		
	Low Level Laboratory (C)	Medium Level Laboratory (B)	High Level Laboratory (A)
Very high	10 µCi	10 µCi to 1mCi	1 mCi
High	1 mCi	1 mCi to 100mCi	100 mCi
Moderate	100 mCi	100 mCi to 10 Ci	10 Ci
Slight	10 Ci	10 Ci to 1000 Ci	1000 Ci

9.2 Details of Types of Laboratories

9.2.1 High Level Laboratory

Grade A level laboratories are for handling levels of activity not usually encountered in a hospital. The most hazardous operation normally followed in a hospital

is dispensing therapy doses (80-200 mCi) of ^{131}I for the treatment of carcinoma of the thyroid. Should labelling procedures with ^{125}I or ^{131}I be undertaken they may also involve multimillicurie quantities of these radionuclides. These activities can be safely carried out in a Grade B laboratory.

9.2.2 Medium Level Laboratory

The main features of a Grade B or medium level laboratory are listed below:

1. Specifically set aside for handling radionuclides.
2. Protective clothing used including gowns or overalls, gloves and overshoes.
3. Negative pressure with extraction fans to the outside of the building to prevent spread of contamination inside the building.
4. Fume hoods, including a glove box.
5. Floors, walls and benches should be smooth and without cracks and must have nonabsorbent, washable surfaces.
6. Benches should be strong enough to support lead shielding.
7. Wash basin with elbow and or boot operated taps.
8. Sink with direct access to the main drain for disposal of radioactive liquid waste.

9.2.3 Low Level Laboratory

The low level or Grade C laboratory is suitable for all tracer work and for simple operations with millicurie quantities of the less hazardous isotopes. Any conventional chemical laboratory having floors covered with linoleum may be used. Workbenches should be provided with nonabsorbent tops and disposable covers. There should be a fume hood with a fan and the exhaust air should be carried outside the building but need not be filtered. Work surfaces should be strong enough to support lead shielding.

Table 6. Radionuclides of Very High Toxicity

ACTINIUM 227	PLUTONIUM 240
AMERICIUM 241	PLUTONIUM 241
AMERCIUM 243	PLUTONIUM 242
CALIFORNIUM 249	POLONIUM 210
CALIFORNIUM 250	PROTACTINIUM 213
CALIFORNIUM 252	RADIUM 223
CURIUM 242	RADIUM 226
CURIUM 243	RADIUM 228
CURIUM 244	THORIUM 227
CURIUM 245	THORIUM 228
CURIUM 246	THORIUM 230
LEAD 210	URANIUM 230
NEPTUNIUM 237	URANIUM 232
PLUTONIUM 238	URANIUM 233
PLUTONIUM 239	URANIUM 234

Table 7. Radionuclides of High Toxicity

ACTIUM 228	EUROPIUM 154	STRONTIUM 90
ANTIMONY 124	HAFNIUM 181	TANTALUM 182
ANTIMONY 125	INDIUM 144M	TELLURIUM 127M
ASTATINE 211	IODINE 124	TELLORIUM 129M
BARIUM 140	IODINE 126	TERBIUM 160
BERKELIUM 249	IODINE 131	THALLIUM 204
BISMUTH 207	IODINE 133	THORIUM 234
BISMUTH 210	IRIDIUM 192	THULIUM 170
CADMIUM 115M	LEAD 212	URANIUM 236
CALCIUM 45	MANGANESE 54	ZIRCONIUM 95
CERIUM 144	PROTACTINIUM 230	
CESIUM 134	RADIUM 224	
CESIUM 137	RUTHENIUM 106	
CHLORINE 36	SCANDIUM 46	
COBALT 56	SILVER 110M	
COBALT 60	SODIUM 22	
EUROPIUM 152	STRONTIUM 89	

Table 8. Radionuclides of Moderate Toxicity

ANTIMONY 122	IRIDIUM 194	RUBIDIUM 86
ARGON 41	IRON 52	RUTHENIUM 97
ARSENIC 73	IRON 55	RUTHENIUM 103
ARSENIC 74	IRON 59	RUTHENIUM 105
ARSENIC 76	KRYPTON 85M	SAMARIUM 151
ARSENIC 77	KRYPTON 87	SAMARIUM 153
BARIUM 131	LANTHANUM 140	SCANDIUM 47
BERYLLIUM 7	LEAD 203	SCANDIUM 48
BISMUTH 206	LUTETIUM 177	SELENIUM 75
BISMUTH 212	MANGANESE 52	SILICON 31
CADMIUM 109	MANGANESE 56	SILVER 105
CADMIUM 115	MERCURY 197M	SILVER 111
CALCIUM 47	MERCURY 197	SODIUM 24
CARBON 14	MERCURY 203	STRONTIUM 85
CERIUM 141	MOLYBDENUM 99	STRONTIUM 91
CERIUM 143	NEODYMIUM 147	SULFUR 35
CESIUM 131	NEODYMIUM 149	TECHNETIUM 96
CESIUM 136	NEPTUNIUM 239	TECHNETIUM 97M
CHLORINE 38	NICKEL 63	TECHNETIUM 97
CHROMIUM 51	NICKEL 65	TECHNETIUM 99
COBALT 57	NIOBIUM 93M	TELLERIUM 125M
COBALT 58	NIOBIUM 95	TELLERIUM 127
COPPER 64	OSMIUM 185	TELLERIUM 129
DYSPROSIUM 165	OSMIUM 191	TELLERIUM 131M
DYSPROSIUM 166	OSMIUM 193	TELLERIUM 132
ERBIUM 169	PALLADIUM 103	THALLIUM 200
ERBIUM 171	PALLADIUM 109	THALLIUM 201
EUROPIUM 152M	PHOSPHORUS 32	THALLIUM 202
EUROPIUM 155	PLATINUM 191	THORIUM 231
FLUORINE 18	PLATINUM 193	THULIUM 171
GADOLINIUM 153	PLATINUM 197	TIN 113
GADOLINIUM 159	POTASSIUM 42	TIN 125
GALLIUM 72	POTASSIUM 43	TUNGSTEN 181
GOLD 196	PRASEODYMIUM 142	TUNGSTEN 185
GOLD 198	PRASEODYMIUM 143	TUNGSTEN 187
GOLD 199	PROMETHIUM 147	VANADIUM 48
HOLMIUM 166	PROMETHIUM 149	XENON 135
INDIUM 115M	PROTACTINIUM 233	YTTERBIUM 175
IODINE 125	RADON 220	YTTRIUM 90
IODINE 130	RADON 222	YTTRIUM 92
IODINE 132	RHENIUM 183	YTTRIUM 93
IODINE 134	RHENIUM 186	ZINC 65
IODINE 135	RHENIUM 188	ZINC 69M
IRIDIUM 190	RHODIUM 105	ZIRCONIUM 97

Table 9. Radionuclides of Slight Radiotoxicity

ARGON 37	RHODIUM 103M
CESIUM 134M	RUBIDIUM 87
CESIUM 135	SAMARIUM 147
COBALT 58M	STRONTIUM 85M
GERMANIUM 71	TECHNETIUM 96M
HYDROGEN 3	TECHNETIUM 99M
INDIUM 113M	THORIUM 232
IODINE 129	NATURAL THORIUM
KRYPTON 85	URANIUM 235
NICKEL 59	URANIUM 238
NIOBIUM 97	NATURAL URANIUM
OSMIUM 191M	XENON 131M
OXYGEN 15	XENON 133
PLATINUM 193M	YTTRIUM 91M
PLATINUM 197M	ZINC 69
RHENIUM 187	ZIRCONIUM

10. SAFETY PROCEDURES FOR THE HANDLING OF RADIOISOTOPES

10.1 Introduction

Radiation exposure can arise from direct external irradiation from a source, or from contamination of the working area with radioactive materials. Internal irradiation may arise from the inhalation or ingestion of radionuclides.

There are two fundamental principles that underlie radiation safety: to minimize radiation exposure to the persons handling the activity and to prevent the spread of contamination outside the laboratory.

The safety rules for the handling of radioactive materials in the laboratory are as follows:

10.2 General Safety Precautions

1. A specific person should be assigned the responsibility of enforcing safe practices in the work with radioactive material, with the name and phone number of the responsible person shown clearly on the door.
2. Keep the laboratory locked when not in use.
3. Keep all unauthorized persons out of the laboratory.
4. Do not eat, drink or smoke in the laboratory.
5. Do not pipette radioactive solutions by mouth.
6. Do not work with radioactive materials if abrasions of the skin are present.
7. Use rubber gloves whenever there is a chance of contamination.
8. Wear laboratory coats which must be monitored before leaving the laboratory.
9. Wear a dosimeter if required by licence.
10. Use a fume hood or glove box for any work with dry powders or volatile substances.
11. Use disposable absorbent liners on trays or other work surfaces.
12. Glassware used for radioactive work must not be used for other purposes.
13. Monitor equipment and supplies before removing them from the laboratory.
14. Monitor, and if necessary decontaminate equipment, trays, floor and working surfaces on a regular basis, and when work is completed.
15. Wash hands, and when appropriate, monitor throughly before leaving the building.

10.3 Storage and Waste Disposal

1. Mark waste containers and storage facilities for radioactive material with a radiation warning symbol and indicate date, nature, and amount of material on the waste containers.
2. Store radioactive material in a safe shielded place.
3. Do not dispose of any waste without approval from the person in charge.

10.4 Accidents

1. Comply with the local building emergency procedures.
2. Take immediate steps to confine contamination and restrict entry of persons.
3. Notify the person in charge.

Certain basic rules apply to all work with radiation and three points should be remembered: time, distance and shielding.

10.5 Exposure Time

The shorter the time of exposure the less the dose received. Procedures should be practised with inactive materials and all operations with radioactive sources should be carried out as rapidly as is consistent with the satisfactory and safe performance of the task.

10.6 Distance

Radiation intensity at any point is inversely proportional to the square of the distance from the source i.e., the dose rate at 2 metres from the source is only one quarter of that at 1 metre. In all operations involving the use of radioisotope sources, advantage should be taken of the safety provided by distance. This becomes particularly important for a specific operation involving the handling of an unshielded source. Use of longhandled tools for such operations is absolutely necessary.

10.7 Shielding

Shielding with some material which will absorb a large proportion of the radiation is necessary when the work cannot be carried out quickly enough or at such a distance that the radiation is reduced to an acceptable level. The amount and type of shielding will depend on the type and intensity of the source and are discussed in other chapters.

10.8 Sealed Sources

In summary, the following precautions should be observed for the handling of sealed sources:

1. Sealed sources should be regularly examined for contamination, damage, or leakage. The interval between examinations will depend on the nature of the source and type of use involved. If damage is suspected the source should be returned to the supplier immediately with appropriate precautions.
2. Sources should be used under the supervision of a qualified person.
3. Sources should be handled in such a way that the radiation dose is reduced to a minimum by such methods as limited working time, distance and shielding.
4. Detailed survey should be made and warning signs posted. Leakage radiation arising from partially shielded sources should be indicated. The device should be appropriately marked with warning signs.
5. Long-handled tools and temporary shielding should be used if the source itself has to be handled. In such situations, shielding should be placed as near as possible to the source.
6. The radioactive device should be protected against damage. If damage is suspected it should not be used unless it is inspected by a qualified person and found to be safe.
7. All personnel working in the vicinity of a radioactive device should be made aware of the potential hazards and procedures to be followed in case of emergency.
8. All persons likely to receive significant amounts of exposure should wear personal dosimeters.
9. When not in use, devices containing radioactive sources should be stored in a locked shielded enclosure around which the radiation levels are less then 0.25 mr/hr.

10.9 General Health Precautions

1. Protective Clothing

The degree of protection to be provided by protective clothing is a function of the activity used. Even tracer amounts must be handled with laboratory coats or protective gowns over normal attire. When routine radiochemical or biological work is done, overalls or other clothing should be worn. Protective clothing used in active areas should not be worn elsewhere. This should apply even at very low levels in order to avoid contamination of other work.

Plastic or rubber gloves should be worn when handling active materials and such gloves should not be used for handling other items, even in the active laboratory. It should be noted that, whilst gloves will prevent contamination from emitters such as C-14 and S-35 (soft beta radiation) from reaching the skin, they do not stop hard rays or tritiated compounds. Accordingly, high doses may be received by the skin if strong sources are picked up with gloved hands.

Special cloth (or rubber) overshoes should be used if there is a possibility that radioactive material may be spilled on the floor. In some cases, the provision of shoes to be used only in the laboratory is preferrable.

2. Personnel Monitoring

Instruments are necessary to detect the presence of radiation. Every laboratory using open sources of radioactive material should have a survey instrument suitable for the qualitative estimation of contamination.

When gamma-emitting sources of 100 mCi or more are used, there should be an ionization chamber of the rate-meter type, for measuring the intensity of the radiation field.

Personnel monitoring devices should be worn by all persons who might receive more than three tenths the maximum permissable dose of radiation. The thermoluminescent dosimeter is the usual form of personnel monitoring device and is suitable for personnel working with gamma rays and X-rays. Pocket dosimeters are worn for short periods of time and are used to determine immediately the dose received.

It is sometimes possible to measure radiation outside the body from radionuclides present inside the body. The measurement can be made to detect radionuclides in a particular organ or in the whole body by a whole body monitor. For instance, by measuring gamma radiation over the neck the amount of iodine 131 in the thyroid may be estimated. The whole body monitor is a useful tool both in cases of contamination and in research investigations.

One of the most useful procedures in the biological monitoring of personnel is the analysis of urine samples. However, the rate of urinary excretion of a radionuclide reflects only the rate at which that nuclide is leaving the body through the kidneys. This may or may not reflect the amount retained in the body. The relationship between the amount of radioactivity in the body and the amount excreted in the urine varies according to the metabolism of the nuclide, the size of the intake and the solubility of the material.

3. Contamination Control

All work with unsealed radionuclides should be done over a tray lined with absorbent material. Work involving spray, fume or gas evolutions should be done in a hood. When work is completed, each person should individually clean any contaminated material, and if necessary, arrange for its disposal. Trays and bench surfaces should also be cleaned after work. The hands should be thoroughly washed and monitored before leaving the laboratory.

A routine system of contamination survey should be established using appropriate instruments and techniques for the particular material involved. Attention should be paid not only to possible contamination of the laboratory itself, but also to the people and articles leaving the laboratory.

An essential feature of contamination control is regular and proper cleaning of the active area. Cleaning should be done by someone aware of the need for taking precautions. Ordinary janitorial services are usually not suitable for this purpose.

4. Emergency Procedures

In the case of a spill of radioactivity the action will depend on the activity involved and the radiotoxicity of the radionuclide. Equipment should be kept readily available for use in emergency in any department where significant amounts of activity are handled. The essential items will depend on the type of work being carried out but will include protective clothing, decontamination materials, warning signs, equipment for the handling, temporary storing and disposal of contaminated articles, and portable monitoring equipment.

When the accident has involved injury to staff or patients, first aid must be administered. At the same time a person knowledgeable in protection, such as a health physicist, must be called and the Radiation Safety Officer or equivalent notified.

The next concern is to stop the spread of contamination and clear people from the area of a spill. Care should be taken to ensure that people leaving the site are not contaminated.

Decontamination of persons takes priority over cleaning up spills.

A spill is treated as a minor spill if the amount of radioisotope involved falls within the range of quantities that can be used in a low level laboratory. There is negligible hazard to personnel.

Absorbent paper should be laid immediately over a wet spill. Wet absorbent paper should be laid over the affected area in the case of a dry spill. The papers should

then be removed to a suitable waste receptacle and the affected area of the laboratory monitored. Decontamination should then be carried out until the surface is free from removable activity. Swabbing should always be done inwards towards the centre of the spill and the immediate locality of the spill should be decontaminated before attention is given to slight contamination in surrounding areas.

Major spills involve amounts of isotopes greater than those used in low level laboratories.

Such a spill is considered an emergency, but appropriate action will vary according to circumstances. Local regulations for dealing with major spills must therefore be drawn up and posted in laboratories.

11. SAFETY REQUIREMENTS FOR SEALED BETA AND GAMMA RAY SOURCES

11.1 General Requirements

A. All beta- and gamma-ray sources must meet the requirements for sealed sources.

B. Every source should be identifiable and, where practicable, information regarding the nature and activity of the nuclide and the date of manufacture should be marked on the source.

C. Adequate records should be maintained of all sources and their movements to minimize the possibility of loss and the resulting hazards. Loss or suspected loss should be reported immediately to the radiation protection officer.

D. Unauthorized access to sources should be prevented.

E. Attention should be given to the radiation hazards that may arise in the event of fire.

F. Tests for contamination or leakage should be carried out periodically. Defective sources should not be used until satisfactorily repaired.

G. Where sources are liable to release radioactive gas, the place of storage should be effectively ventilated before it is opened.

11.2 Beta-Ray Sources

A. Beta-ray sources not permanently installed in a device should be adequately protected during storage and transport.

B. Where required, shields and baffles should be provided to ensure adequate protection. All source manipulations should be done by remote means.

C. It should be recognized that all beta-ray sources, whether designed for it or not, will emit bremsstrahlung. Other types of penetrating radiation such as gamma-rays, characteristic X-rays and annihilation radiations, may also be emitted. The associated hazards should be evaluated and the necessary precautions taken.

D. Sources intended for the utilization of the beta-rays require a thin window. This window and its mounting should be so constructed as to minimize the possibility of the escape of radioactive material. When not in use the window should be covered by a shield of sufficient thickness to stop all the beta radiation. This shield should preferably be metal of low atomic number to minimize bremsstrahlung production. Shields of metal are recommended as they are less susceptible to radiation damage than, for example, plastics. If necessary an outer shield of high atomic number should be provided to attenuate the bremsstrahlung. The source should not be subjected to rough

and unnecessary handling and should not be exposed to the action of abrasive or corrosive materials. In cleaning the window care should be taken to prevent its damage and to minimize irradiation of personnel.

11.3 Gamma Ray Sources for Medical Use

Where the gamma rays only are to be used, the enclosure for the radioactive material should, whenever practicable, be sufficently thick to absorb substantially all the beta-rays.

11.3.1 Therapy with Non-Collimated Sources

1. General Requirements

(a) When neither in use nor in transit, sources and applicators incorporating sources should be kept in a protective enclosure of such material and wall thickness to ensure that no person is subjected to more than the maximum permissible dose rates.

(b) The protective enclosure should be constructed in such a way as to minimize the exposure of personnel handling the sources. Important factors to consider are the distribution of the sources, the shielding of sub-divided amounts and the time required by personnel to remove sources from the enclosure and return them to it.

(c) Sources should be transported within the establishment in such a manner that all individuals are adequately protected. Account should be taken of the actual transport time but allowance must be made for other possible exposure to radiation. Subject to the foregoing, where the total activity of the sources in a container is low, it may be transported by hand provided it has a sufficiently long handle. Loaded receptables used for the transport of sources should be distinguished by suitable markings and should either be under surveillance or be inaccessible to unauthorized persons.

(d) A separate room or designated space should be provided for the preparation of sources and applicators. During such preparation only those persons engaged in this work should be allowed in these areas.

(e) The preparation, sterilization and dismantling of applicators and sources, involves manipulation with incomplete shielding. It is necessary, therefore, to use proper tools to ensure the minimum irradiation of the body. These tools should be constructed so as to provide the optimum relation between distance and time. Dummy capsules, clearly identified as such, should be used until a high degree of skill has been achieved.

(f) Tables used for manipulating sources shall be provided with protection for the operator and for other persons associated with the work. An L-shaped block of lead or of other heavy material may be used to reduce the irradiation of the body and legs of the operator, but safeguards are still necessary to prevent overexposure of the hands, arms and face.

(g) During the application of sources to patients, distance and exposure time are the most important factors in minimizing radiation hazards. Appropriate instruments and implant devices should be used.

(h) Both ambulatory and bed patients should be segregated into wards or rooms where properly trained personnel are available. The bed, cubicle, or room should be suitably identified during irradiation.

(i) Patients with removable sources in or upon their bodies should not be permitted to leave the hospital or clinic.

(j) Consideration should be given to the protection of other patients and staff.

11.3.2 Beam Therapy (Teletherapy)

1. The appropriate type of teletherapy protective source housing should be used.
2. The use of source capsules of standard design is recommended.
3. The beam control mechanism should be constructed so that it is capable of acting in any orientation of the housing. In addition to an automatic closing device the apparatus should be so constructed that it can be turned off manually with a minimum risk of exposure.
4. The closing device should be so constructed as to return automatically to the "off" position both at the end of an exposure and in case of any breakdown or interruption of the activating force, and should remain in the "off" position when the force is restored until operated from the control panel.
5. The beam control mechanism should be provided with a timer that automatically terminates the exposure after a pre-set time.
6. Warning devices that plainly indicate whether the apparatus is "on" or "off" should be provided at the source housing, on the control panel, and at the entrance to their radiation room.
7. Only the patient should be allowed in the treatment room during irradiation. At all other times the treatment room should be occupied only for necessary purposes associated with the operation and maintenance of the device.

8. Interlocks should be provided so that when any door to the treatment room is opened, the beam control mechanism will return to the "off" position.

9. Means should be provided for observing the patient and for oral communication with the patient from the control panel during the treatment.

12. SAFETY REQUIREMENTS APPLICABLE TO X-RAY INSTALLATIONS

12.1 General Requirements

A. Shielding and Protective Barriers

1. Shielding and protective barriers should be provided so radiation workers do not receive more than 100 mr/week when the unit is operating at its maximum potential.

2. Adequate protection should be provided so that non-radiation workers in areas surrounding the X-ray unit do not receive more than 10 mr/week when the unit is operating at its maximum potential.

3. Occupancy factor should be considered in calculating the accumulated dose. The workload of the unit and any further expansion should also be taken into account. Scattering from the patient should also be considered but attenuation provided by the patient should be disregarded. Structural protection requirements can be reduced by using protective tube housings and imposing restrictions on the orientation of the useful beam.

4. The control panel for the X-ray unit should be located in a separate booth, so arranged that the radiation has to be scattered at least twice before entering the booth. An observation window should be provided in the control booth wall so as to provide a convenient unobstructed view of any area where a patient may be placed during diagnosis or treatment.

5. For equipment operating at 125 kVp or over, movable shielding should not be depende upon.

6. In all protective barriers, care should be taken to ensure that the protection is not reduced at joints, nails, bolts, etc. In such places, there should be an adequate overlapping of the protective material. Holes in the protective barriers for pipes, conduits, louvers, etc., should be provided with baffles so that the protection is not impaired.

7. There should be no unncessary openings from the X-ray room to occupied areas, other than those required under routine working conditions.

8. In large installations, consideration should be given to the possibility of multiple exposure from several different X-ray tubes.

9. The final plans of an installation should indicate the type of material and the dimensions of all protective barriers. The position of all windows, doors, pipes and louvers should be indicated insofar as they affect the protection requirements.

B. Surveys

1. Routine operation of any X-ray installation should be deferred until a radiation survey has been made.

2. A survey should be made following any changes in working conditions or protective barriers.

3. Periodic checks should also be made to ensure that the levels of radiation are within the prescribed limits.

4. When conducting a survey all protective devices (gloves, aprons, etc.), interlocks and warning signals should be inspected. Operating techniques should also be studied and, if necessary, recommendations given to minimize radiation hazards. Personnel monitoring techniques should also be inspected.

5. Radiation measurements should be taken both inside and outside the controlled area. Any defects are to be eliminated before the unit is put into routine use.

C. Protection of Personnel

1. Only qualified persons or persons under the direct supervision of a qualified person should operate the X-ray unit.

2. Dosimeters should be worn by personnel working in the vicinity of an X-ray unit who may be potentially exposed.

D. Protection of the Patient

1. There should be clear-cut clinical indications before any X-ray examination is undertaken, and enquiry made concerning any previous radiological examination which would make further examination unnecessary.

2. There should be consultation between clinician and radiologist before extensive or repeated radiological examinations of young individuals are undertaken.

3. Special precautions should be adopted in the case of pregnant women. Only essential examinations should be carried out during pregnancy and particular care should be taken to avoid irradiation of the foetus whenever possible. In radiography of the pelvic area in women of child-bearing age, the possibility of an early pregnancy should not be overlooked.

E. Miscellaneous

1. Warning signs should be posted on the X-ray room door - "X-RAYS - DO NOT ENTER".
2. Permanent records of all exposures should be kept.
3. Machines having an output of more than 1000 r/min at any accessible place should not be left unattended without the power being shut off at the primary source.

12.2 Medical Diagnostic X-Ray Installations

A. General Requirements

1. Equipment

(a) A diagnostic-type protective tube housing should be used.

(b) Apertures, cones or shutters which serve to limit the useful beam should provide the same protection as the tube housing.

(c) For most diagnostic installations a protective barrier having a lead equivalent thickness of 1/16 inch to a height of 7 ft. should be adequate.

(d) The permanent total filter should be determined by the highest voltage of the X-ray unit. Equipment with a maximum operating potential above 70 kVp should have a permanent total filter equivalent to at least 2mm of aluminum. Equipment with a lower maximum operating potential should have a permanent total filter equivalent to at least 1.5 mm of aluminum.

(e) A dead-man type of exposure switch should always be used where practicable.

(f) Photoelectric timers or similar devices should be used. Where these are not practicable, accurately pre-set timing devices should be used.

(g) The fastest films and screen consistent with satisfactory diagnostic value should be used.

B. Radiological Procedures and Techniques

(a) The integral dose to the patient should be kept to a minimum.

(b) Strict limitation of field size to the area necessary for the particular examination or treatment should be routinely practiced. This should be done by fitting light beam diaphragms rather than circular cones, particularly when a large field size is used.

(c) Whenever possible, the beam should not be directed towards the gonads and this should be borne in mind particulary in examinations of the limbs, especially of the hands with the patient in the sitting position.

(d) Adequate gonad shields should invariably be used in examinations or treatments which are likely to give a high gonad dose, unless they interfere with the proposed examination.

(e) In the examination of children or patients who need support, mechanical devices to ensure immobilization should be used. If necessary, children should be held by their parents or assistants other than X-ray room personnel. These people should be given adequate protection especially to the gonads and the hands through the use of leaded screens, aprons and gloves.

C. Fluoroscopy

1. Equipment

(a) The X-ray tube and fluorescopy screen should be so linked that the screen cannot be moved out of the useful beam.

(b) The fluorescent screen should be covered with a protective glass sheet having a lead equivalent of at least 2.0 mm for 100 kVp X-rays. From 100 to 150 kVp an additional lead equivalent of 0.01 mm per kilovolt is required. (This includes the attenuation of the patient). Image intensifiers should afford the same protection.

(c) A switch for controlling the X-ray beam should be provided at the fluoroscopic screen.

(d) A manually reset cumulative timing device should be provided which will either indicate the total time of irradiation or terminate the irradiation when the total time exceeds a previously determined time.

(e) All couches and stands for fluoroscopy work should be provided with an adequate arrangement for protecting the operator and his assistants against scattered radiation, particularly from the patient and the underside of the table top. This may take the form of an apron attached to the screen or couch in such a way as to provide maximum protection. The minimum dimensions of this apron should be 18 inches square with a lead equivalent of not less than 0.5 mm.

(f) It is recommended that a "high-low" milliampere switch be provided, the low current should be used to locate the site of interest and the high current to explore the area quickly.

(g) The so-called hand fluoroscope should not be used.

2. Radiological Procedures and Techniques

(a) The focus-skin distance should not be less than 45 cm (18 inches) for voltages over 100 kVp or 30 cm (12 inches) for voltages less than 100 kVp.

(b) During fluoroscopy protective aprons and gloves should be worn for X-rays produced at voltages up to 100 kVp. The gloves cover the whole hand including the back, palm, fingers and wrist. The aprons and gloves should have a lead equivalent of not less than 0.25 mm, and should be checked periodically for cracks.

(c) Before a fluoroscopic examination is begun, the eyes must be sufficiently dark-adapted. In order to work with the lowest possible dose rate, the adaptation period should be at least 10 minutes.

(d) For routine fluoroscopy, the exposure rate measured at the panel or table top should be as low as possible and should not exceed 10 r/min.

(e) Fluoroscopy should not be undertaken if the same information can be obtained by radiography.

D. Radiography with Fixed Equipment

1. A light-beam localizer for indicating the cross-section of the useful beam should be used.

2. A device should be provided to terminate the exposure after a pre-set time or exposure.

3. The X-ray exposure should be controlled from the control panel only, except in the case of special techniques when it may be necessary to control it from the stand or couch.

4. The patient should be observable from the control panel without requiring the operator to leave the shielding of the control area.

5. Only one patient should be examined at any one time in the same room.

E. Mobile Radiography Equipment

1. All mobile equipment should be provided with collimating cones or diaphragms and spacer frames to ensure that the focus-skin distance is not less than 30 cm (12 inches) and that the useful beam is limited to the minimum size required for the examination.

2. The minimum distance of the operator from the tube and patient should be 1.5 m (6 feet).

3. The operator should take all possible precautions to ensure that persons in the vicinity of the X-ray equipment are not irradiated.

4. Fluoroscopy should not be carried out unless the requirements of section 12.2 Part C are satisfied.

5. The dose rate to the patient should not exceed 10 r/min. at 12 inches.

F. Photo-Fluorography (Mass Radiography)

1. A collimator should restrict the useful beam to the area of the fluorescent screen. The use of a light-beam localizer should be used for this purpose.

2. Shielding should be such that all personnel in the vicinity of the equipment are adequately protected during routine use, without the necessity for protective clothing.

3. The use of high-speed optical systems, which enables the dose to the patient to be reduced, is recommended.

4. Chest examinations of pregnant women should not be carried out with mass miniature techniques.

5. Chest examination of children and adults of short stature should not be carried out with mass miniature techniques unless special devices are used to shield the gonads.

6. In order to minimize the population dose, consideration should be given to the protection of persons awaiting examination.

G. Dental Radiography

1. Localizing cones should be employed with all dental equipment. Such cones should provide the maximum practicable focus-skin distance (7 inches minimum for 50 kVp or over and 4 inches minimum for 50 kVp or less), and the minimum practicable field size (3 inch diameter maximum).

2. A timer should be provided to terminate the exposure after a pre-set time. The timer cord should be of sufficient length to assure that the operator may remain outside the main beam.

3. Installations operating up to 70 kVp should be so arranged that the operator can remain at least one meter (70 kVp and over, at least 1.5 meters) from the tube and patient.

4. For installations exceeding 30 ma-min/week, protective screens having a lead equivalent of not less then 0.5 mm should be used.

5. Shielding should be provided to protect persons in adjacent areas, especially if more than one dental unit is operating in the same area.

6. Whenever possible, the film should be fixed in position. It may be held by the patient or some person accompanying the patient provided the person is not occupationally exposed to radiation. It should never be held by the dentist or his staff, who should under no circumstances be exposed to the useful beam.

7. Fluoroscopy with dental equipment should not be used.

8. For equipment operating up to 70 kVp, the total permanent filtration should be equivalent to 1.5 mm Al.

9. The exposure control switch should be of the dead-man type.

10. The tube housing or pointer cone should not be held by hand during exposure.

11. A lead apron and thyroid shield should be worn.

12.3 X-Ray Therapeutic Installations

A. General Requirements

1. A therapeutic-type protective tube housing should be used.

2. Permanent diaphragms or cones used for collimating the useful beam should provide the same degree of protection as the tube housing. Adjustable or removable beam defining diaphragms should not transmit more than 5% of the useful beam.

3. All removable filters should be clearly marked with their thickness and material. These markings should be recognizable from the control panel.

4. A mark on the tube housing should show the location of the focal spot.

5. Unless it is possible to rapidly bring the X-ray output to the prescribed value, the tube housing should be fitted with a shutter electrically operated from the control panel and of lead equivalent not less than that of the tube housing. The position of the shutter should be indicated at the control panel.

6. The equipment should be provided with an automatic timer to terminate the treatment after a pre-set time.

7. Means should be provided for observing the patient and should be provided for oral communication with the patient from the control panel during the treatment.

8. For installations operating above 100 kVp interlocks should be provided so that when any door to the treatment room is opened the X-ray equipment will shut off automatically and can only be turned on again from the control panel.

9. A transmission monitoring chamber in the useful beam is recommended for observing the constancy of the radiation. The dose rate of the useful beam should be given by a calibration chart giving the dose rate at specified kVp, Ma, filters, size of applicator and focus-skin distance. These charts should be frequently checked against an ionization chamber.

10. For installations, operating above 100 kVp, only the patient should be in the treatment room during irradiation.

13. PRINCIPLES OF RADIATION DETECTION

13.1 Introduction

Ionizing radiation unlike light or heat cannot be detected by our normal senses. Consequently it is necessary to have instruments which will detect the presence and measure the quantity of the various types of radiations emitted by radioactive materials, X-ray machines, particle accelerators and nuclear reactors.

13.2 Purpose of Measurement

Radiation measuring instruments are used for a variety of purposes. They can be classified into the following main categories:

A. Laboratory instruments for measuring the radioactivity of a sample.

B. Survey instruments for measuring the exposure rate in a radiation field.

C. Personnel monitoring instruments for measuring total cumulative exposure.

13.3 Methods of Measurement

There are various principles for the detection of radiation - of these the following are the most important and commonly used:

1. Electrical collection of ions
2. Photographic detection
3. Scintillation of crystals
4. Chemical decomposition
5. Fluorescent and thermoluminescent detectors
6. Calorimetric detectors
7. Recoil and nuclear reactions for neutron dosimetry

13.4 Electrical Collection of Ions

Radiation detection instruments based on the principle of collection of ions formed in a gas comprise the vast majority of instruments in use. The most common of these are:

1. Ionization chambers
2. Proportional counters
3. Geiger counters

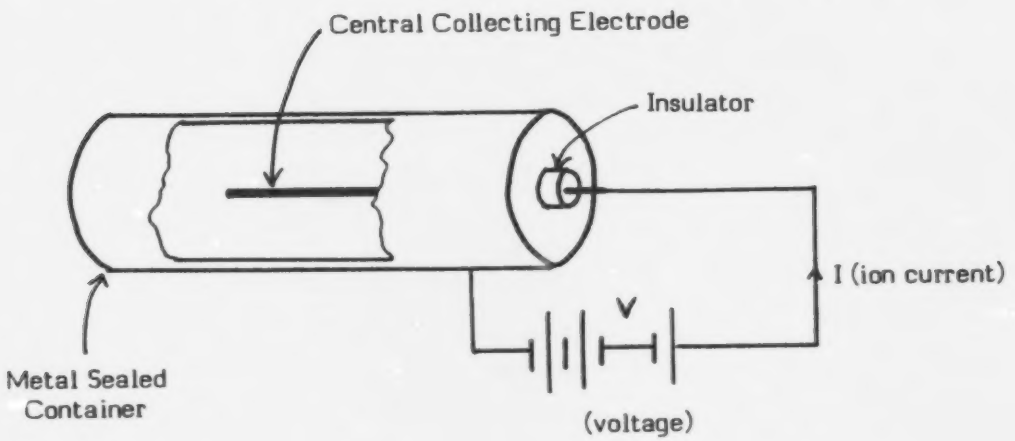
13.4.1 Ionization Chambers

When radiation interacts with a gas, ions are produced. These ions eventually recombine. However, if an electrical field is present the ions will tend to be attracted to the oppositely charged surfaces. This is the principle of an ionization chamber.

An ionization chamber is essentially a cylindrical chamber fitted with a central electrode and filled with gas, usually air at standard temperature and pressure. A voltage is applied between the outer case and the central electrode. This serves to attract the appropriate ions to the charged surfaces and results in a flow of current.

As the voltage is increased fewer ions tend to recombine until a stage is reached where all the ions created are collected by the electrode. This voltage results in operation in the chamber in the saturation current region. Measurement of the current passing through the chamber is therefore directly proportional to ionization and hence the radiation intensity.

Figure 18. Ionization Chamber



Operating voltage for an ionization chamber instrument usually varies between 60 and 300 volts depending upon the size of the chamber and the filling gas. The instruments operating on this principle have low sensitivity since they measure only the primary ionization produced. For the same reason they measure high radiation fields. They are not suitable for discrimination between several types of radiations.

13.4.2 Proportional Counter

If the voltage is increased above that required to give saturation current flow, the ions in moving toward the electrodes gain sufficient energy to cause secondary

ionization thus giving rise to a larger number of ions. For every ion pair formed by the initial radiation, a much larger number is received by the electrodes. This phenomenon is called gas amplification. Increase of voltage raises the gas amplification factor. The size of the pulse recorded on the instrument is thus proportional to the voltage and to the number of primary ions formed if the voltage is kept constant. The pulse size gives an indication of the difference of ionization and hence the type of radiations. For example an alpha-particle which gives intense ionization will give a larger pulse than a gamma-ray photon which produces only a few primary ions.

The region of operation of a gas chamber is called the proportional region. In proportional counters, gas amplication factors as high as 10^6 are sometimes employed. Proportional instruments provide a high sensitivity and a high range. The instruments are very suitable for discriminating between α and β particles. Commercial counters are filled with argon, methane or a mixture of the two, though air is sometimes used. Operating voltages range from 500 to 5000 volts.

13.4.3 Geiger-Mueller Counters

With further increase of voltage the gas amplification factor greatly increases resulting in a veritable avalanche of electrons to the anode of the chamber. The resulting pulse height is relatively independent of the specific ionization of the initiating particle or photon. This region of operation is called the Geiger-Mueller region. The gas amplification factor can be as high as 10^{10} and the instrument is extremely sensitive and consequently can detect radiation which produces even one ion pair. Because of this feature it is not possible to distinguish radiations of different energies using a Geiger tube.

During the discharge of the positive ions at the cathode of the Geiger tube, secondary radiations may be generated. These can cause secondary pulses or even set up a continuous discharge in the tube. This phenomenon can be avoided by a variety of methods.

Geiger tubes are usually filled with an inert gas such as argon or helium at about 0.1 atmosphere. Once a tube is discharged it must be quenched in order that other particles may be detected. This quenching can be done by an electronic circuit from which the high voltage is removed as soon as the discharge occurs. Self-quenching tubes are now used in which quenching gases are introduced into the argon filled counters. For large tubes, gases, such as ethyl alcohol are used. It has also been found that halogen gases are very good quenchers and they are now being used because of their longer life as opposed to organic-agent quenched tubes. Because of the quenching action a G-M tube is inoperative for a very short time interval after each pulse.

This is called the "dead time". The dead time is an important consideration only when high rates of counting are involved.

A Geiger tube works in the region indicated in Figure 19. This region has a flat section known as a "Geiger plateau" in which variation in voltage does not cause variations in count rate. It is usually preferable to operate a Geiger tube in approximately the center of the Geiger plateau. Beyond the Geiger plateau is the region of continuous discharge, i.e., the tube will continue to discharge once a discharge is initiated. This, if allowed to continue is damaging to the tube. Commercially available tubes operate at voltages between 1000 and 3000 volts.

13.5 Photographic Detection

Darkening of photographic emulsion by radiation was the first method used for detecting nuclear radiation. When radiation strikes photographic film it ionizes the silver halide in the emulsion. The effect is so small that there is no visible sign of any change in the exposed film. However upon development the latent image is converted into a black deposit of metallic silver. This darkening may be related to the type, energy and quantity of radiation received on the film.

Photographic methods for radiation detection and measurement are most useful in the investigation of nuclear tracks. The most extensive use however is in making radiographs as in X-ray diagnostic work and in autoradiography where the exact location of a radioisotope within a complicated structure can be pinpointed.

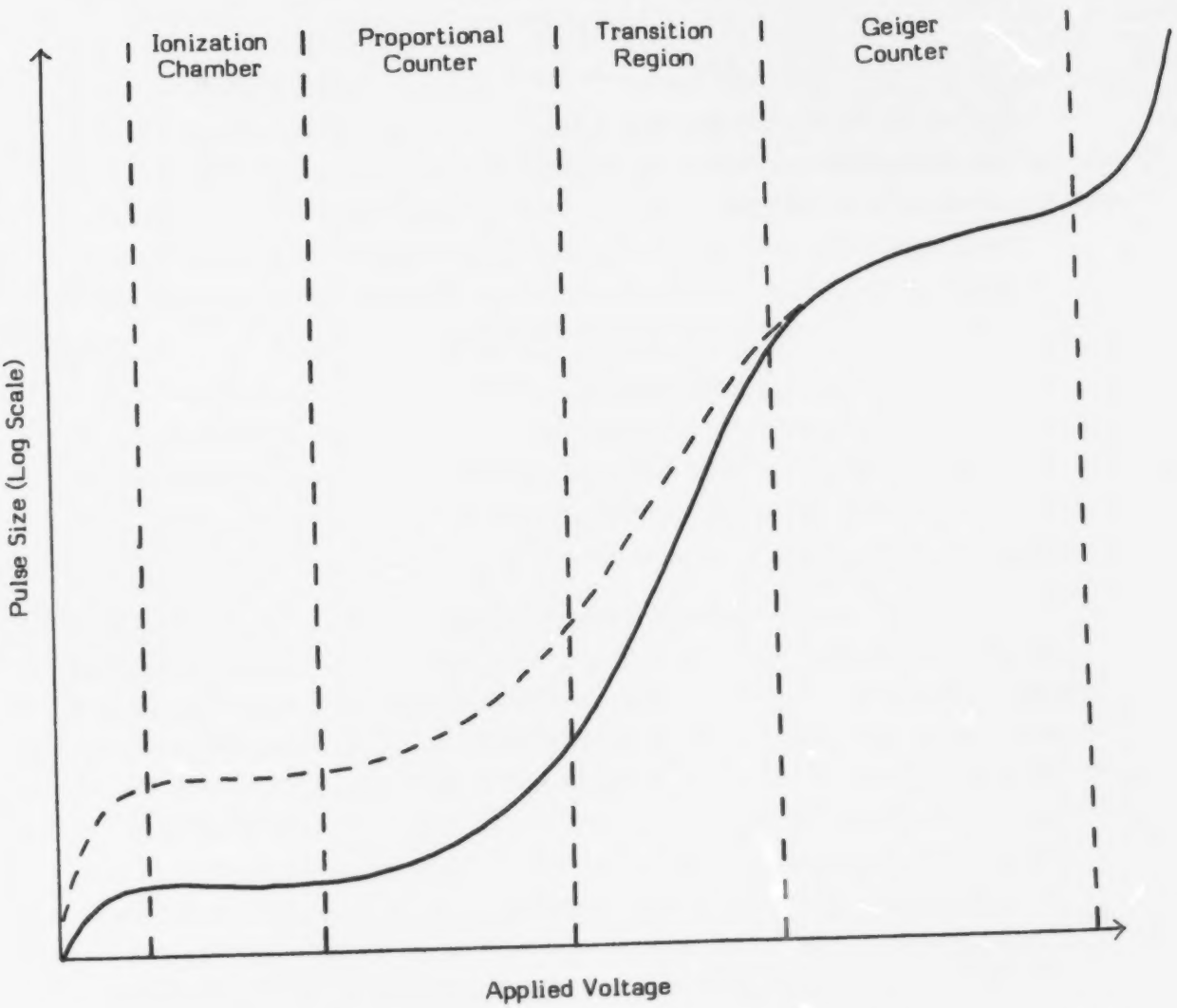
13.6 Scintillation of Crystals

Various materials, when struck by radiation, convert part of the absorbed energy to visible light. Such materials are called phosphors. There are many materials in nature which exhibit this phenomenon. Many ores and minerals give off a fluorescence when exposed to ultraviolet light. Sodium iodide crystals containing small amounts of certain impurities have excellent scintillating properties. For every γ-ray photon interacting with such a crystal, a photon of light is emitted. The magnitude of this light pulse is proportional over a wide range, to the energy of the radiation. Further the sodium iodide is transparent to the light emitted and allows it to be seen by a detector placed in close proximity. In a scintillation counter the scintillating crystal is mounted on a photomultiplier tube and the whole assembly sealed to render it light proof.

The photomultiplier tube is made up of a photocathode and a number of dynodes. A light pulse entering the tube strikes the photocathode and ejects electrons, the number of electrons ejected being proportional to the intensity of the light. The dynodes

are maintained at a increasing voltage differential so that the electrons move from one to the next with increasing acceleration and amplification. The result is an appreciable energy pulse at the output of the photomultiplier. This amplified pulse may be further amplified and fed into a counter.

Figure 19. Variation of Pulse Size With Applied Voltage



Various types of phosphors are in use. While sodium iodide is commonly employed for gamma radiation, silver activated zinc sulphide is not suitable for α-particles. The latter phosphor requires a large amount of energy transfer per crystal, to produce the necessary light output. Hence it is insensitive to most radiations other than α-particles. Anthracene is useful for the measurement of β-radiation although other substances such as naphthelene and stilbene are also in use. Transparent plastic materials impregnated with phosphor are finding increasing use for many purposes.

Scintillation dectectors have a number of advantages over the ionization type instrument:

A. The ability to detect different types of radiation by changing the phosphor used.

B. Their high sensitivity specially for gamma radiations.

C. Ability to measure high activities without loses due to dead time.

D. The possibility of using them as spectrometers for determination of the energies of the incident radiation.

13.7 Chemical Decomposition

Radiation causes ionization and in certain mediums such ionization can initiate chain reactions. Chain reactions in a chemical system serve the same functions as an amplifier in an electric circuit.

Chemical reactions initiated as a result of radiation are of various types. The main ones are:

A. Oxidation-reduction reactions.

B. Changing the pH of the solution.

C. Initiation of polymerization reactions.

A good example of the first type is the Fricke dosimeter. This consists of a dilute solution of ferrous sulphate which on absorption of radiation changes to ferric sulphate. The amount of ferric sulphate produced is proportional to the amount of radiation absorbed and can be determined by measuring the absorption of a certain wave length of light (305 mμ).

A typical chemical decomposition indicator is a mixture of chloroform and water which produces hydrochloric acid in proportion to the radiation absorbed. The consequent change in pH can be seen with built-in indicators.

Radiation can induce polymerization in most monomers. It also can produce degradation in polymers. Potentially both these reactions can be used for measuring radiation dose. The former phenomenon usually results in the monomers solution becoming more viscous. A measurement of viscosity gives a direct indication of radiation dose. There are unending possibilities in this method of dosimetry.

Chemcial dosimetry can be made very accurate when the absorbed dose is to be measured. They are not sensitive for low doses of radiation, neither is it possible to use them for rapid determination of radiation dose rates. They are essentially a research tool useful for calibrating other types of instruments.

13.8 Fluorescent and Thermoluminescent Detectors

13.8.1 Fluorescent Dosimeters

Certain materials if subjected to ionizing radiation store the energy absorbed and release it in the form of light if subjected to ultraviolet radiations. This phenomenon is called radiophotoluminescence. The amount of energy emitted in the form of visible light is proportional to the amount of initial exposure to ionizing radiations and can therefore be used for dosimetry.

Silver-activated phosphate glass used in commercially available instruments are suitable for measuring up to 100 000 rads. Some recently developed dosimeters can measure as low as 30 mr. For using such dosimeters specially designed and calibrated instruments are required.

13.8.2 Thermoluminescent Dosimeter (See Chapter 14)

Dosimeters of this type are very similar to the phosphate-glass dosimeters but instead of ultraviolet light, luminescence is induced by heating the phosphor at a specific temperature. Lithium fluoride is a very suitable phosphor for this purpose. It is usually used as a powder encased in a small capsule. This type of dosimeter also requires an elaborate read-out instrument.

13.9 Calorimetric Determination

Radiation energy when absorbed in material is eventually converted to heat energy, thus, the rise in temperature in the material being irradiated can be used to measure radiation dose. The method is very insensitive and difficult to use as an energy absorption of 100 rads/min produces in material of unit specific heat, a temperature rise of only 2.5×10^{-4}° C/min.

13.10 Recoil and Nuclear Reactions (Neutron Dosimetry)

Neutrons do not ionize material through which they pass, neither do they have any charge of their own. Hence the principles used for their detection have to depend on secondary reactions. Further, the nature of their reaction with matter is greatly dependent on their kinetic energy. This makes it necessary to utilize different principles for each range of energy.

In practice neutrons are classified as slow if their kinetic energy is less then 20 kV. All others are fast.

13.10.1 Slow Neutrons

Slow neutrons interact with matter by capture reactions. In the human body the reactions of importance are:

$$^{1}H + ^{1}n \longrightarrow ^{2}D$$

$$^{14}N + ^{1}n \longrightarrow ^{14}C + ^{1}H$$

Slow neutrons react with Boron-10 to produce Lithium-7 as follows:

$$^{10}B + ^{1}n \longrightarrow ^{7}Li + ^{4}He$$

The fast moving helium or α-particle causes intense ionization and can thus be detected. A detector of ionizing radiation having boron-lined walls and filled with borontrifluoride gas if operated in the proportional region is suitable for detecting slow neutrons.

For detecting a large number of slow neutrons, activation of foils is employed. Materials such as gold with large capture cross sections become radioactive and then can be detected. Short-lived radioisotopes are quite suitable. A similar reaction is the production of Na-24 from natural Na-23. This reaction is used to measure massive exposures to humans since sodium is a constituent of the blood.

13.10.2 Fast Neutrons

Fast neutrons lose their energy by collisions with other atoms. The most effective material for slowing down neutrons is one which contains a large proportion of hydrogen. Water and paraffin are commonly used.

To detect fast neutrons a detector of ionizing radiation can be surrounded by paraffin and the recoil protons, produced by collisions with the neutrons, counted. By use of pulse-height detectors and operating in the proportional region, the pulses due to the protons can be identified.

The boron-fluoride counter used for slow neutrons, if surrounded by paraffin is also suitable for counting fast neutrons. Here the neutrons are first slowed down and then undergo the nuclear reaction with boron.

Fast neutrons can be detected and counted by nuclear emulsion photographic films. The recoil protons give rise to tracks in the film and these can be seen under a microscope.

Various nuclear reactions have been used for the detection and estimation of fast neutrons. Some of these take advantage of the fission reactions with natural uranium. Others, take advantage of capture reactions, such as that with sulphur:

$$^{32}_{S} + ^{1}_{n} \longrightarrow ^{32}_{P} + ^{1}_{p}$$

This latter reaction has been used to determine fast neutron dose to humans. The sulphur content of the hair in this case is the built-in indicator.

14. PERSONNEL DOSIMETRY

14.1 Introduction

Personnel monitoring instruments are desgined to measure the cumulated absorbed dose received by a person. These instruments are different from survey instruments which normally measure the radiation exposure rate only.

The Radiation Protection Bureau has provided a dosimetry service on a national scale since 1951. Until recently a photographic film dosimeter was used but in 1976 the Thermoluminescent Dosimetry (TLD) System was introduced. Thermoluminescence is now the most widely used principle for personnel dosimetry and is an efficient and reliable method of evaluating radiation exposures.

14.2 Personnel Dosimetry

A personnel dosimeter normally consists of a detector and a holder for the detector. The following characteristics are desirable for personnel dosimeters:

(a) response is either energy independent over the desired range or an indication that the quality of radiation is feasible;

(b) low response to radiation that falls outside the desired range and quality;

(c) low fading of registered dose;

(d) integration of dose received over a period of time;

(e) ruggedness, ease of wear, may be shipped by mail, and is tamper proof;

(f) identification is possible;

(g) low response to change in direction of incident radiation, and environmental parameters, such as humidity, temperature, illumination, chemicals, electromagnetic and acoustic radiation;

(h) rapid estimation of dose.

A. Advantages

1. Provides a permanent record of the exposures received by the user.
2. Has a wide range starting at a few mr up to 10^3 mr.
3. Can be re-used many times.
4. Dose readout possible within 15 minutes of receipt of plaque.

B. Disadvantages

1. Accuracy low for exposures less than 10 mrem.
2. Sensitive to dirt and grease.
3. Does not provide direct information of contamination by radioactive material.

14.3 Thermoluminescent Dosimetry (TLD) System

The objectives of this service are:

(a) to estimate personal doses received by radiation workers and to keep records of doses in a form commensurate with compliance requirements specified for the protection of each radiation worker;

(b) to report to subscribing organizations doses received individually by each member of a subscribing group;

(c) to draw to the attention of the pertinent managers and federal or provincial agencies, the dose records of those radiation workers whose cumulative doses have exceeded the recommended limits and of those who have suffered acute irradiation under accident conditions;

(d) to provide service through postal delivery;

(e) to ensure that dose estimates are in units such that the recorded doses may be summed together;

(f) to supply radiation workers with a well designed personnel dosimeter or a set of these to meet the objectives of the service.

14.3.1 Thermoluminescence and Glow Curves

Thermoluminescent materials are available in various forms, each of which has advantages and disadvantages in personnel dosimetry.

Compacted chips of thermoluminescent materials produce more consistent results than powder, rods or other forms. They are suitable for large-scale routine personnel dosimetry, because of ease of handling and re-usability.

Upon passage of ionizing radiation through a thermoluminescent chip, some of the electrons in the material are released from the atoms and molecules in the chip. Free electrons may become "trapped" at locations where impurities, i.e., foreign atoms are present and may remain in the metastable state indefinitely at room temperature. When a chip is heated, the "trapped" electrons return to the ground state and photons of visible light may be emitted during the transition. Thus, some of the radiation energy, during an exposure, is stored in the chip and is released on subsequent heating. The release is accompanied by emission of visible light and is generally

called thermoluminescence. The total amount of light emitted during the glow period is a measure of the amount of radiation received earlier. The curve of light output vs the temperature (at constant heating rate) is called the glow curve.

In applications of TL materials to personnel dosimetry, it is generally the integral value of light output (as measured by a photomultiplier) that is used. The glow curves are normally examined during the setting up of the reading instruments, testing the chip batches, and during periodic calibration checks.

The shape of a glow curve depends upon many factors, including the heating rate and its uniformity, the conductivity, size and shape of the phosphor, the quality of the incident radiation, the radiation and annealing history of the sample, the level of exposure, the characteristics of the recording instruments and the PM tube, the composition of the TL material, etc.

14.3.2 Whole Body and Skin Dosimeter

The Radiation Protection Bureau provides two types of dosimeters, one for monitoring doses to the whole body and skin and the other for monitoring doses to the extremities of the body. Hands, arms, feet, legs, or head, are often closer to a source of radiation than the main part of the body and receive greater exposure. For this reason an additional dosimeter is sometimes necessary.

The dosimeter consists of a plaque and a plaque holder. The plaque is made of an aluminum stamping and has the same length and width as the personnel monitoring film. It has two holes with the face of each hole covered by an adhesive "kapton tape". Two lithium fluoride thermoluminescent chips (one in each hole) are mounted on this tape. The holder consists of an outer sleeve and an insert designed to accept the plaque in only one orientation.

Dosimeters worn for monitoring whole body or skin dose should be worn at the waist or lapel position. For monitoring dose received at extremities of the body, a separate extremity dosimeter may be worn. This dosimeter consists of a plastic ring with a circular indentation to hold a thermoluminescent lithium fluoride chip and is normally worn on the finger.

14.4 Comparison of Dosimetric Qualities of TL Lithium Fluoride and Photographic Films

Thermoluminescent lithium fluoride has both advantages, and disadvantages compared to photographic films, for personnel dosimetry. Essential aspects are tabulated below primarily from the standpoint of large-scale routine personnel dosimetry.

Parameters	TL Lithium Fluroide	Photographic Film
1. Tissue Equivalence and Energy Response:	Effective Atomic Number is close to that of air and tissue, and therefore, calibration in roentgens for X-rays and gamma rays allows estimation of mrem values within a few percent of tissue dose, over a wide range of energy.	Effective Atomic Number is appreciably different from that of air, and response is significantly more energy dependent than for lithium fluoride.
2. Response to Beta Rays and Low Energy Photons:	Same calibration factor as that for gamma rays is valid within ± 20% for photons, and electrons up to 10 MeV energy.	The calibration factor varies widely with energy.
3. Number of Detectors required:	Two detectors, one for whole body dose and the other for skin dose, are generally satisfactory.	Response from more than two areas of detectors is necessary for energy identification.
4. Mixed Radiation Exposure:	Dose accuracy within ± 20% for mixtures of electrons and gamma rays generally.	Accuracy varies widely depending on the composition of the mixture.
5. Response to UV and incandescent light:	Small.	Very high.
6. Special Packaging:	Not important.	Very critical.
7. Size:	Small.	Larger sizes are required.
8. Dose Range:	Millirem to 10^5 rem. Accuracy low for exposures less than 10 mrem.	Millirem to 10^3 rem. Accuracy high for less than 10 mrem for diagnostic X-rays, but low for Cs-137 gamma rays.
9. Fading:	About 5% in one year. Independent of room temperature and humidity. Suitable for extended monitoring periods up to one year.	Half-life may be less than one year at room temperature and humidity. Not suitable for extended monitoring periods.
10. Dose Rate Dependence:	Negligible.	Negligible.
11. Re-usability:	Can be re-used many times.	Cannot be re-used.
12. Linearity of Response:	Linear up to 10^3 rem. Supralinear above 10^3 rem.	Requires a film pack containing more than one type of film to maintain linearity to 10^3 rem.

13.	Retention of Dose information after Readout:	Not possible. Dose readout data are retained from records of registered dose.	Possible by careful storage of processed films for many years of storage time.
14.	Diagnostic Information:	Limited with two detectors.	Possible with more than two suitable filters over separate areas of the same film.
15.	Computer Interpretation of Dose:	Simple because of linearity over the wide dose range.	Complicated because of non-linearity of dose response with energy of exposure.
16.	Plaque Identification:	Automatic.	Not easily automated.
17.	Dirt and Grease:	Sensitive.	Not sensitive.
18.	Interference from Tritium:	Small.	Large.
19.	Useful Information:	Does not provide direct information of contamination by radioactive material.	Provides vivid information of radioactive contamination and guidance to good housekeeping.
20.	Emergency Monitoring:	Dose readout possible within 15 minutes of receipt of plaque.	Dose readout possible within several hours of receipt of film.
21.	Shipment by Mail:	Suitable for Shipping and receiving by mail.	Suitable for shipping and receiving by mail.
22.	Reporting Speed:	Routinely within twenty-four hours of receipt of used dosimeters.	Routinely within several days of receipt of used dosimeters.

14.5 Pocket Dosimeter

The self-reading pocket dosimeter is the most useful of the other types of personnel dosimeters. It looks and is carried like a fountain pen.

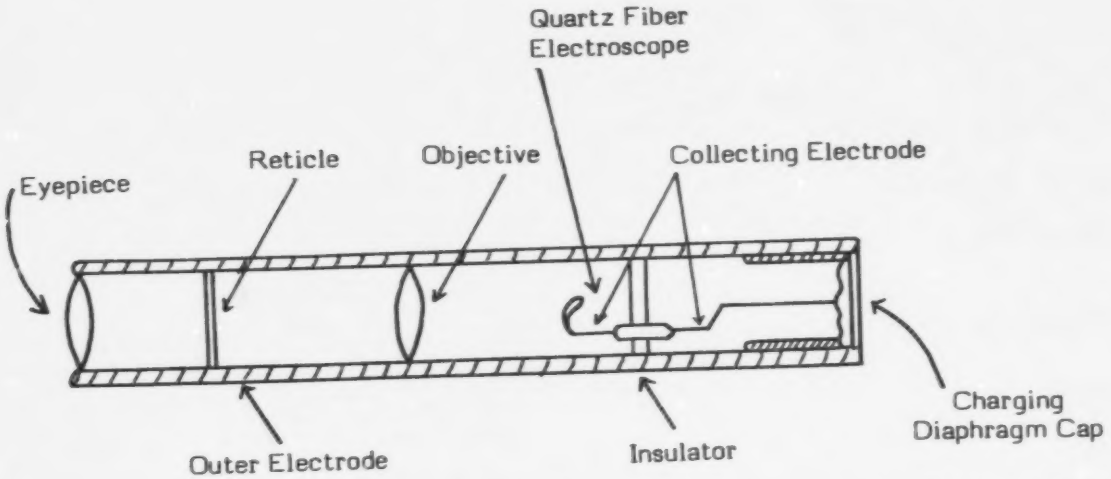
Inside the barrel is a quartz fibre and a wire, each bent into a "U" and joined at the ends to form a conducting system. A built-in microscope with a transparent scale is focussed on the center of the bend in the quartz fibre.

When an electric charge is applied to the system, the quartz fibre is repelled from the bent wire. This happens because two bodies with similar charge repel each other. The dosimeter is now charged and reads "Zero" on the scale.

One way of discharging the dosimeter is by making the air inside conducting. This can be done by ionizing this air with radiation. The amount of discharge would

show up as a movement of the quartz fibre, since this would tend to fall back to its original position. This movement which can be read on the scale and is a measure of the amount of radiation which caused the ionization.

Figure 20. Pocket Dosimeter



This type of dosimeter is basically an ionization chamber. It has certain advantages and disadvantages as follows:

A. Advantages

1. It is fairly robust and does not need too much care for maintenance.
2. It is small and can be clipped on easily to clothing or any part of the body.
3. It is weather proof and does not have to be protected from rain or sun.
4. It can be read any time and anywhere by the user and thus gives an indication of the dose received immediately after exposure.

B. Disadvantages

1. There is no way of finding out the quality of the radiation.
2. It has a very limited range usually less than 1 Roentgen.
3. It does not provide a permanent record since they can be charged and discharged at will.
4. It can give false readings under many circumstances, e.g., being dropped on a hard floor.

15. PRINCIPLES AND MATERIALS USED FOR REDUCING RADIATION EXPOSURES

There are certain basic principles for the protection of personnel, regardless of the type or energy of the radiation. The main factors to be considered are time of exposure, distance and shielding. The most economical and practicable combination of these factors consistent with adequate protection should be used.

15.1 Time

Time is the most effective factor in reducing radiation exposures in many cases. The time a person must spend near a radiation source can often be reduced by careful planning. Procedures that can be done in the shortest possible time should always be adopted.

15.2 Distance

Distance is very effective and can be one of the easiest and cheapest factors to apply. Alpha and beta particles do not travel far in air, and distance is the most effective shielding for them. For X- and γ rays the intensity decreases very rapidly with the distance between the point source and the point of interest. This relationship is expressed by the Inverse-Square Law which is written as

$$\frac{I}{I_o} = \frac{D_o^2}{D^2}$$

Where, I_o is the original intensity
I is the "new" intensity
D_o is the original distance
D is the new distance.

15.3 Shielding

Shielding is the most important and expensive of the three factors for protecting personnel. Shielding allows intense or large sources to be used in working areas where personnel must remain for long periods of time. The principle of shielding is straightforward, and concepts have been introduced to make the calculation of shielding requirements very simple. These are HVL and TVL. It should be noted that the values of these vary as radiation penetrates a thick shield. This variation is caused by the build-up within the absorber, and hardening of the beam. This last point is particularly evident when dealing with X-ray beams but the errors introduced can be greatly reduced by using TVL when dealing with thick absorbers.

15.3.1 Factors to Consider in Shielding Computations for X-ray and Gamma Ray Installations

A. Occupancy Factor (T)

The term occupancy factor is used to denote the fraction of the total possible time that a person is required to remain in the given area under question. The handbooks have laid down a number of standard occupancy factors which can be used in calculating permissible fields at various locations. These occupancy factors are as follows:

1. Full Occupancy (T = 1)

   This factor is used in control spaces, offices, waiting rooms large enough to hold desks, darkrooms, workshops, nursing stations, lounges, living quarters or play areas used by children.

2. Partial Occupancy (T = 1/4)

   Used for corridors too narrow for desks, utility and rest rooms, lounges not used routinely by occupationally exposed personnel, elevators and unattended parking lots.

3. Occasional Occupancy (T = 1/16)

   Can be used for closets, too small for future occupancy, toilets not used routinely, stairways, automatic elevators, outside areas used only for pedestrian or vehicle traffic.

The use of the occupancy factor is a practical application of the "time factor". By reducing the length of time which a person is required to spend in a certain location it is possible to increase the permissible radiation fields in that location by an appropriate factor. The occupational limits of 5 mrem/year, 100 mrem/week and 2.5/hour are all based on an occupancy factor of 1. For example, in a small broom closet, adjacent to a radiation installation the occupancy factor can be assumed to be 1/16. The allowable fields in this broom closet could thus be as high as 40 mrem/hour.

B. Use Factor (U)

In some cases the term "Use Factor" (U) is used in calculating permissible fields.

1. Full Use (U = 1)

   Would be areas such as the floors of a radiation room, walls or ceiling exposed full time to the direct beam.

2. Partial Use (U = 1/4) and (U = 1/16)

Would be walls, ceiling, etc., exposed only part of the working time to the direct beam. In determining the thickness of shielding barriers, the use factor should be considered. The "Use Factor" is most commonly used in X-ray work.

C. Workload (W)

Another factor to be considered is the workload which for X-ray installations is expressed ma/minute/week.

15.3.2 Shielding Materials

In considering the shielding which is required for certain installations or devices it is wise to keep in mind a number of important factors which have a bearing on the cost of the installation. The choice of shielding material, the location of the shielding in relation to the radiation source, and the configuration or shape of the shield are important. In order to compare various shielding materials, only a few of the more common types in use will be considered here.

A. Lead

Lead is undoubtedly the most common, well-known and widely used material for shielding X-and γ radiation. Because of its high atomic number, (82) the photo-electric effect and Compton effect (which are the two most important processes over the energy range of interest) are very effective, and the reduction of the primary beam is very high. Also the scatter from lead is lower than from materials which have lower atomic numbers.

A few of the main drawbacks with lead are the fact that it has a fairly low melting point and also tends to creep at room temperatures. These factors limit the structural value of lead and therefore, any lead shielding must be substantially supported. This is particularly true for thick sheets of lead on walls. Some of the more important constants for lead are listed in the Table below.

Table 10. Constants for Lead

Density	11.34 gm/cm
μ (1.2 MeV)	0.74 cm^{-1}
Melting point	621°F
HVL (Co-60)	1.244 cm
HVL (400 kVp X-ray)	.223 cm
HVL (250 kVp X-ray)	.812 cm
HVL (100 kVp X-ray)	.025 cm

B. Concrete

For large sources and installations, concrete is probably the most economical and practical of all shielding materials. It has good structural properties, does not creep or melt and can be easily poured in almost any configuration desired. Solid concrete blocks or double concrete block walls, filled with sand or stone can also be used to good advantage. The one disadvantage of concrete is that its shielding properties are not as good as lead, and once a concrete wall has been poured in a certain location it is not easy to change it. For portable devices, concrete is out of the question because of its bulk. Some of the more important constants for concrete are listed in the next Table.

Table 11. Constants for Concrete

Density	147 lb/ft^3
μ (1.25 MeV)	$0.13\text{-}1$
Melting point	Very high
HVL (Co-60)	6.858 cm
HVL (400 kVp X-ray)	3.302 cm
HVL (350 kVp X-ray)	2.794 cm
HVL (100 kVp X-ray)	1.778 cm

C. Iron and Steel

These two materials are used for shielding in certain circumstances. They are a little more efficient than concrete but not as good as lead. Iron and steel cannot be formed into odd shapes too easily and the cost is usually too high in comparison with the amount of shielding provided.

Some of the more important constants for iron and steel are shown below.

Table 12. Constants for Iron and Steel

Density	7.8 gm/cc
μ (1.25 MeV)	0.4 cm^{-1}
Melting point	2800°F
HVL (Co-60)	2.209 cm
HVL (400 kVp X-ray)	2.54 cm
HVL (250 kVp X-ray)	.939 cm
HVL (100 kVp X-ray)	.254 cm

D. Depleted Uranium

Depleted uranium has found use as a shielding material in the past few years. It has a higher atomic number than lead, therefore, for X- and gamma rays it is a more efficient absorber. The density of Uranium is 19.05 gm/cc and it melts at 2070°F.

E. Lead Glass

As the name suggests this glass contains lead salts. It is commercially available in various densities. The shielding properties of some lead glasses are shown below.

Table 13. Shielding Properties of Lead Glass

2.54 cm (1 inch) of Hi-D glass (6.2 density) equals	1.397	cm	lead
	2.54	cm	steel
	1.112	cm	concrete
2.54 cm (1 inch) of Me-D glass (3.8 density) equals	.863	cm	lead
	1.371	cm	steel
	4.318	cm	concrete
2.54 cm (1 inch) of Lo-D glass (3.0 density) equals	.660	cm	lead
	1.066	cm	steel
	3.302	cm	concrete

The cost of lead glass is very high and therefore, its use is limited to situations where direct viewing is essential.

15.4 Considerations in Shielding Configurations

As mentioned earlier, various shields have various properties when related to the different radiations. In order to make the maximum use of the shield being employed, it is necessary to understand the mechanisms of attenuation and the advantages and disadvantages of the type of shield being used.

When designing large X- or γ installations it is always advisable to combine distance and shielding to give the most economical configuration.

Open top shielding configurations, that is, large well-shielded rooms which do not have a shielded ceiling, should be situated so that any scattering from the ceiling or machinery above the unit does not reach occupied areas. Lead covered ceilings or collimating of the primary beam can be employed to reduce scattering.

15.5 Radiation Surveys

15.5.1 Introduction

A radiation survey is concerned with the radiation directly absorbed, the scattered radiation, and the leakage radiation from the X-ray equipment, all of which contribute to the patient dose. It is similarly concerned with the radiation scattered outside the patient and any stray primary beam that presents a hazard to the staff, to the general public and to the quality of the radiation image used for diagnosis.

A comprehensive radiation survey should be carried out by a physicist experienced in the field. The radiologist and X-ray technicians should demonstrate their working methods so that the physicist can make recommendations that entail the minimum modifications in the functioning of the department.

15.5.2 Personnel Monitoring

Personnel monitoring, if done routinely, will provide much of the information required for the survey. However, it is subject to certain limitations. Personnel monitoring is discussed in more detail in Chapter 14.

15.5.3 Area Monitoring

Area monitoring is carried out with survey instruments of various types. The most reliable are those using the ion-chamber principle if they are properly calibrated for the energy of the radiation to be measured. In practice, dose rates are measured and by applying the proper correction factors the potential hazard at any given point can be estimated.

15.5.4 Fixed Position Monitoring

Film badges or pocket ionization chambers may be taped or fixed to the walls, doors, protective screens, etc., and used to determine the potential exposures at these locations. By such methods the dose rate over long periods of time can be fairly accurately determined. The monitors are in the radiation field under actual working conditions and therefore do not involve the use of assumed values such as 'workload' and 'use' factors. The monitors must be left in the selected points long enough to represent typical operating conditions.

15.5.5 Survey Instruments

Survey meters are similar to other radiation detection instruments in their operatonal characteristics. A good survey meter should be portable, rugged, sensitive, simple in construction and reliable. All these conditions are not available in any one instrument, but there are many that have most of the desirable features.

X-ray and Gamma Ray Instruments

Survey instruments to accurately measure X-rays and gamma rays must be calibrated to determine:

(i) the energy dependence;
(ii) the directional effects;
(iii) the scale accuracy; and
(iv) the rate dependence.

The energy dependence for these instruments usually is most critical at energies below 100 to 300 keV.

Instruments are designed by manufacturers to read directly in radiation units. However, for the reasons given above, and since the characteristics of individual components cause variations in instrument response, it becomes necessary to calibrate each instrument for the use intended in order to obtain accurate readings.

15.5.6 Survey Report

The results and implications of the survey should be discussed with the head of the department and the radiation protection officer.

A typical survey report is shown in the appendix.

GLOSSARY OF TECHNICAL TERMS

Absorption - The process whereby radiation energy is imparted to matter.

Activity - Rate at which atoms are disintegrating.

Alpha Particles - Often referred to as alpha rays. These are positively charged nuclei of helium atoms.

Annihilation - Occurs when a particle and anti-particle meet. For the positron and electron the result is two photons at 0.51 MeV.

Atomic Number - The number of protons in the nucleus of an atom (Z).

Atomic Weight - The number approximately equal to the sum of the number of protons and neutrons found in the nucleus of an atom (A).

Attenuation - The process by which the radiation field is reduced.

Background - A term used to describe the radioactivity or radiation field of the environment.

Becquerel - S.I. unit of activity = 1 disintegration per second.

Beta Particles - Often referred to as beta rays. These are free electrons ejected from atoms by radioactive decay.

Bremsstrahlung - X-rays produced by electrons subject to rapid deceleration.

Calibration - The determination of deviations from an accepted standard of a measuring instrument to obtain the necessary correction factors.

Carcinogenic - Capable of producing cancer.

Chromosome - Rod-shaped structures of cell nuclei which contain genes.

Chronic Exposure - Irradiation which is spread over a long period of time.

Compton Effect - The phenomenon by which a gamma ray photon interacts with an orbital electron to produce a secondary gamma ray and an electron.

Contamination - As applied to radioactive substances the spread of radioactive material in unwanted areas.

Cosmic Rays - High energy rays received from outer space, part of the natural radiation background.

Counter - A device which responds to the passage of nuclear radiation by means of electronic amplification.

Curie - The old unit of activity = 3.7×10^{10} disintegrations per second.

Daughter - As used in radioactivity, refers to the product nucleus or atom resulting from decay of the parent.

Decay - The spontaneous nuclear process which may result in the emission of alpha, beta, and/or gamma rays. Synonymous with disintegration.

Decontamination - The process of removing radioactive contamination from objects or areas.

Dose - A measure of the amount of radiation absorbed by tissue per unit mass.

Dose Rate - The dose rate delivered per unit time.

Dose Equivalent - A measure of the biological effect of radiation = dose X quality factor. (Sievert)

Dosimeter - An instrument used to determine the radiation dose received by a person.

Electron - The smallest unit of electrical charge. It is the constituent of the outer part of an atom.

Electron Volt - A unit of energy equal to that gained by an electron in passing through a potential difference of 1 volt (eV).

Excited State - Temporary state of a nucleus, atom or molecule intermediate in potential energy between the normal stable state and complete disintegration, ionization or decomposition.

Erythema - Reddening of the skin due to increased local circulation of blood as a reaction to tissue injury.

Exposure - A measure of the amount of ionizing radiation present.

Fission - Splitting of an atomic nucleus into two or more lighter nuclei (fission products). Can be either spontaneous or induced.

Filter - A sheet of metal which is interposed between patient and the source of X-rays to absorb a selective part of the beam.

Fluorescence - Emission of visible light from a crystal after the absorption of energy.

Fluoroscope - A fluorescent screen which is mounted in front of an X-ray tube so that internal organs can be visualy examined.

Gamma Rays - Electromagnetic radiation emitted from the nucleus of an atom during radioactive decay.

Gray (Gy) - S.I. unit of radiation dose = J/kg.

Half-Life - The length of time required for the decay of one half of the atoms in a given sample.

Half Value Layer - The thickness of a specified absorbing material which reduces the dose rate to one-half its original value.

Hot - A colloquial term meaning radioactive.

ICRP - The International Commission on Radiological Protection.

Ion - An atomic particle, atom or molecule with an electrical charge.

Ionization - The process whereby one or more electrons are removed from a neutral atom.

Ionization Chamber - A device roughly similar to a Geiger Counter and used to measure radioactivity.

Ionizing Radiation - Electromagnetic (X-rays, γ rays) or particulate (alpha, beta, neutron, etc) radiation which produces ions as it passes through matter.

Isotopes - Atoms of the same element which have the same charge but different masses.

Kilovolt - A unit of 1000 volts which is used to describe the energy of X-rays (kV).

Kilovolt peak - The maximum value of the potential in kilovolts (kVp). Applies to an X-ray unit.

Latent Period - The time which elapses between exposure and the manifestation of radiation damage.

Mass Number - Total number of protons and neutrons in the nucleus of an atom.

Monitor - To survey the level of radiation in a given area to determine the extent of radiation hazard.

Mutation - The transformation of a gene induced by radiation or other agents which alters the characteristic of the offspring.

Neutron - An elementary nuclear particle with no electrical charge and a mass similar to a proton.

Neutrino - Light uncharged particle emitted during beta decay.

Nucleus - The inner core of the atom.

Nuclide - A particular atomic species distinguished by both its atomic number and mass number.

Overexposure - Radiation exposure beyond the specified limits.

Pair Production - The conversion of a gamma photon into a pair of particles, an electron and a positron.

Parent - A radioactive nucleus which disintegrates to form a radioactive product or daughter.

Photoelectron - Produced when an electron totally absorbs a high energy photon and acquires sufficient energy to escape from its atom.

Photon - Quantum of electromagnetic radiation.

Positron - A particle which has the same weight as the electron and a charge which is equal but electrically opposite.

Proton - An elementary nuclear particle with a positive charge.

Quality Factor - Nominal biological effectiveness of radiation as set by regulatory bodies. Value is 1 for beta, gamma and X-rays, 20 for alpha rays.

Quantum - Synonymous with photon.

Rad - Old unit of radiation dose = 100 ergs/gram.

Radioactivity - The phenomenon whereby atoms disintegrate with emission of radiation.

Radioisotope - Radioactive isotope of an element. Synonymous with radionuclide.

Rem - Old unit of dose equivalent = rads x quality factor.

Roentgen - A unit of exposure dose defined by the amount of ionization produced under specified conditions.

Shielding - The material which is interposed between a radiation source and an irradiated site for the purpose of reducing radiation.

S.I. - Système International. Internationally agreed system of metric units.

Sievert (Sv) - S.I. unit of dose equivalent = Gy x quality factor.

Somatic - Pertaining to all body tissues other than the reproductive cells.

Source - Any substance or object which emits radiation.

Tenth-Value Layer - The thickness of a specified absorbing material which reduces the intensity to one-tenth of its original value.

Ultra-Violet - Electromagnetic radiation more energetic (higher frequency) than visible light but insufficiently energetic to cause ionization.

X-Rays - High energy electromagnetic radiation emitted by electrons when changing energy levels within an atom or when rapidly decelerated.

APPENDIX

SURVEY REPORT

General Information:

Institution: General Hospital

Surveyor: Mr. John Doe Survey Date: May 27/64

Installation Data:

Location: Room No. 3 Main X-Ray Department

Make and Model: Picker-Pictronic 300

Type of Generator: Single-Phase full-wave rectified

Type of Unit: Combined radiographic-fluoroscopic

X-Ray Tubes:

1. Radiographic - Dynamax 25
   (a) Diagnostic tube-housing.
   (b) Equipped with collimator.
   (c) 3 mm. Al. equivalent total filtration.
2. Fluoroscopic - Dynamax 26
   (a) Diagnostic tube-housing.
   (b) Equipped with smoothly operating shutters.
   (c) 3 mm. Al. equivalent filtration.
   (d) 18 inches from focal spot to panel or table top.

Remarks:

The equipment in this room showed no major defects. The following points were noted as being undesirable.

1. The exposure switch cord is 6 ft. long and will permit the operator to stand outside of the protected area to make an exposure.
2. The added filters for the radiographic tube can be removed readily.
3. The junction of the collimator and tube-housing on the radiographic tube does not provide protection equal to that of the tube-housing.

4. The doors to the room are not lead-lined.
5. No device for covering Bucky slot during fluorsocopy.

Recommendations:

1. Operators should be cautioned not to leave the protected area when making exposures.
2. The added filters on the radiographic tube should be installed so that tools are necessary for their removal.
3. Doors should be lead-lined if the present workload is increased.

Table 1 - Direct Beam Measurements

Tube	KVP	MA	*TCP	r/100 mas.	r/minute
Radiographic	70	50	40"	0.58	-
"	80	50	40"	0.76	-
"	90	50	40"	0.95	-
"	100	50	40"	1.1	-
Fluoroscopic	90	3	18"	-	3

*TCD to mean target-chamber distance.

Table 2 - Stray Radiation Measurements
(Radiographic Procedures)

Location of Measurement (see Figure 1)	Direction of Beam	mr/100 mas	Phantom
1. Control booth through glass	Down (centre of table)	0.01	Yes
2. Control booth operator's position	"	0.01	Yes
3. Control booth entrance	"	0.3	Yes
4. Side door (closed)	"	.01	Yes
5. Corridor door (closed)	"	0.4	Yes
6. Darkroom	"	.01	Yes
7. Sorting room	"	.01	Yes
8. Toilet	"	.01	Yes

Table 3 - Stray Radiation Measurements
(Fluoroscopic Procedures)

Location of Measurement (see Figure 1, 2, and 3)	Direction of Beam	mr/hr	Phantom
9. Through Apron	Up (centre of table)	25	Yes
10. Side of table	"	250	Yes
11. Side of table	"	200	Yes
12. Side of table	"	100	Yes
13. Bucky slot	"	10-500	Yes
14. Through corridor door	"	20	Yes
15. Control booth	"	Nil	Yes
16. Through protective glass on fluoroscopic screen	"	85	No
18. To side of "patient"	"	300	Yes
19. Operator's foot position	"	100	Yes
20. Control booth	Horizontal (towards corridor)	Nil	Yes

Figure 1. X-Ray Room No. 3

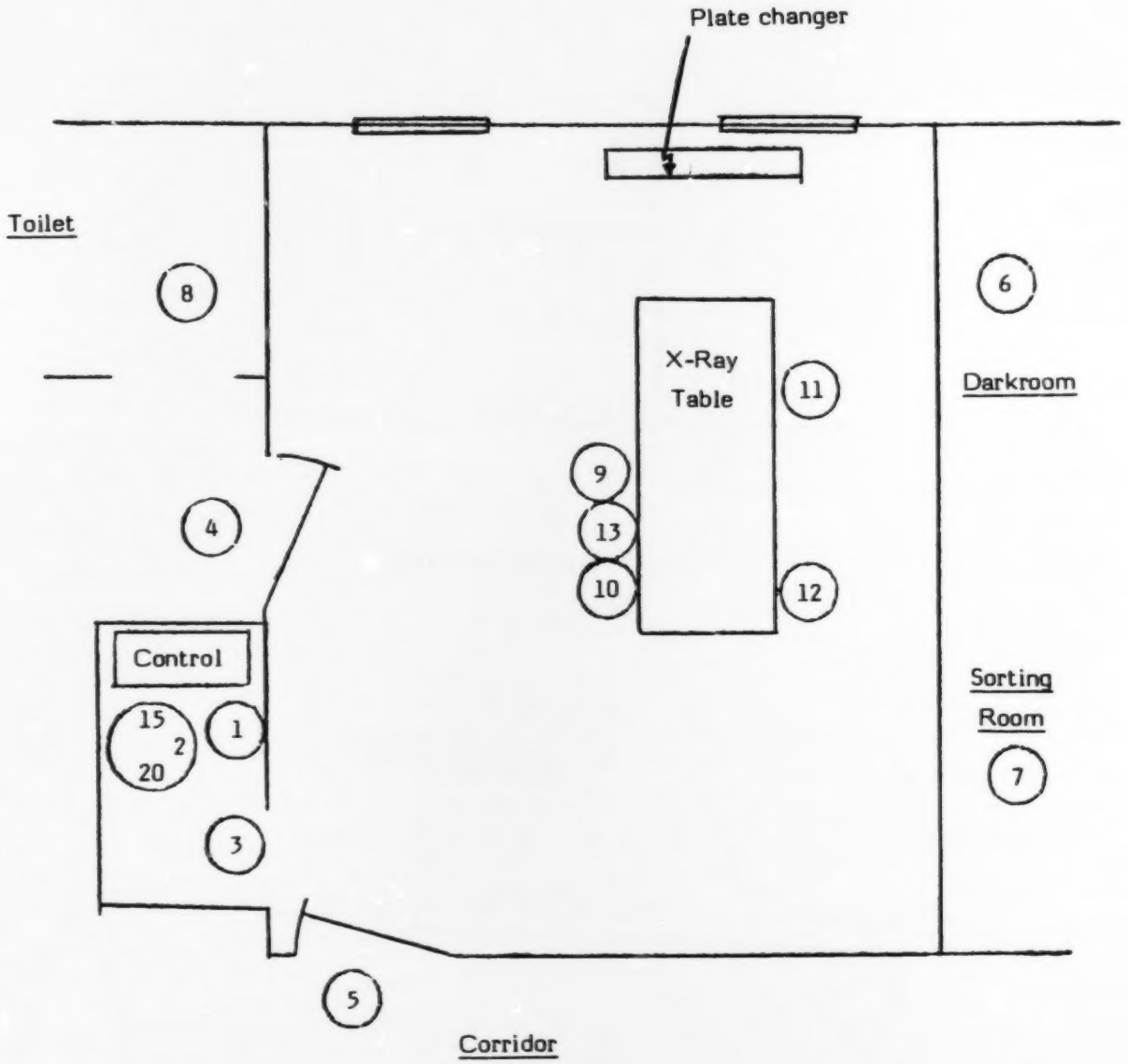


Figure 2. Table in Vertical
X-Ray Room No. 3

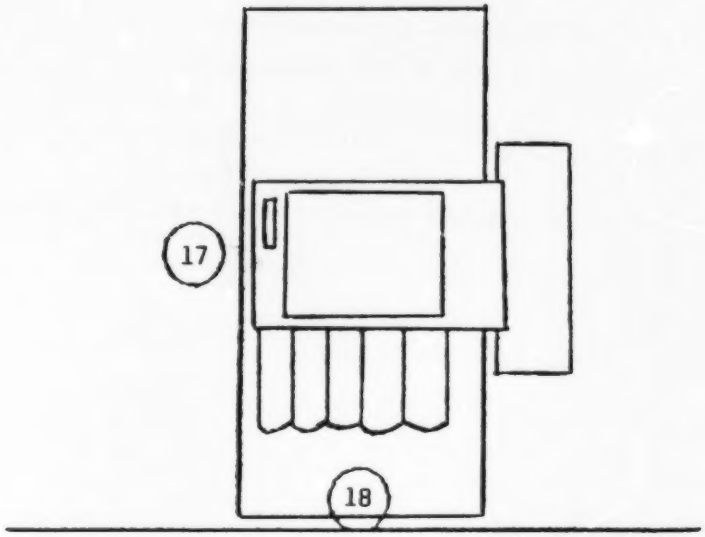


Figure 3. Side View of Table